

Lunar Dust Effects on Spacesuit Systems

Insights from the Apollo Spacesuits

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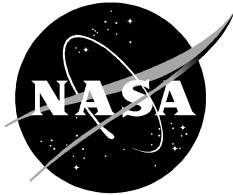
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Acronyms, Symbols and Abbreviations

A7L	Spacesuit Model Number
A7LB	Spacesuit Model Number
BSE	Backscattered Electron Imaging
CDR	(Apollo Mission) Commander
CM	Command Module
CMP	Command Module Pilot
EDS	Energy-Dispersive (X-ray) Spectroscopy
ED-XRF	Energy-Dispersive X-ray Fluorescence
EMU	Extravehicular Mobility Unit
EPMA	Electron Probe Microanalyzer
EV	Extravehicular
EVA	Extra-Vehicular Activity
ILC	ILC Industries, Inc.
ITMG	Integrated Thermal Micrometeoroid Garment
IV	Intravehicular
JSC	Johnson Space Center
LEAP	Light Element Analysis Program
LiOH	Lithium hydroxide
LM	Lunar Module
LMP	Lunar Module Pilot
LRV	Lunar Rover Vehicle
MCI	Museum Conservation Institute
MET	Mission Elapsed Time
MSC	Manned Spacecraft Center
NASDIRT	NASA Smithsonian Dust Investigation Research Team
NASM	National Air and Space Museum
OPS	Oxygen Purge System
PGA	Pressure Garment Assembly
PLSS	Portable Life Support System
ppm	Parts-per-Million
SEM	Scanning Electron Microscopy
TLSA	Torso Limb Suit Assembly
μm	Microns
USSRC	U.S. Space and Rocket Center
WSTF	White Sands Test Facility

Abstract

Systems and components of selected Apollo A7L/A7LB flight-article spacesuits that were worn on the lunar surface have been studied to determine the degree to which they suffered contamination, abrasion and wear or loss of function due to effects from lunar soil particles. Filter materials from the lithium hydroxide (LiOH) canisters from the Apollo Command Module were also studied to determine the amount and type of any lunar dust particles they may have captured from the spacecraft atmosphere. The specific spacesuit study materials include the outermost soft fabric layers on Apollo 12 and 17 integrated thermal micrometeorite garment assemblies and outermost fabrics on Apollo 17 extravehicular pressure gloves. In addition, the degree of surface wear in the sealed wrist rotation bearing from Apollo 16 extravehicular and intravehicular pressure gloves was evaluated and compared. Scanning electron microscope examination of the Apollo 12 T-164 woven Teflon® fabric confirms the presence of lunar soil particles and the ability of these particles to cause separation and fraying of the Teflon fibers. Optical imaging, chemical analysis and particle sampling applied to the outer fabric of the Apollo 17 spacesuit has identified Ti as a potentially useful chemical marker for comparing the amount of lunar soil retained on different areas of the spacesuit outer fabric. High-yield particle sampling from the Apollo 17 fabric surfaces using adhesive tape found 80% of particles on the fabric are lunar soil particles averaging 10.5 μm in diameter, with the rest being intrinsic fabric materials or environmental contaminants. Analysis of the mineralogical composition of the lunar particles found that on a grain-count basis the particle population is dominated by plagioclase feldspar and various types of glassy particles derived mostly from soil agglutinates, with a subordinate amount of pyroxene. On a grain size basis, however, the pyroxene grains are generally a factor of 2 larger than glass and plagioclase, so conversion of the data to a modal (volume %) basis results in pyroxene becoming the modally dominant particle type with glass and plagioclase significantly less abundant. When comparisons are made to the modal composition of lunar soil at the Apollo 17 landing site, the results suggest that pyroxene particles have overall better retention on the spacesuit outer fabric compared to plagioclase and especially glass. Scanning electron microscopy revealed no measurable difference in the amount of wear and abrasion in the wrist rotation bearing of an Apollo 16 pressure glove worn only in the spacecraft and one worn only for extravehicular activity on the lunar surface. The results suggest either that the bearing prevented entry of lunar dust, or that dust was not sufficiently abrasive to damage the bearing, or both.

Introduction

Exploration activities performed on the Moon by both humans and robotic spacecraft occur on a planetary surface comprised of unconsolidated fragmental rock material called the lunar regolith. Although it contains rock fragments centimeters to meters in size, the lunar regolith consists predominantly of much smaller particles, generally less than 1 cm in size, which are conventionally referred to as the lunar “soil” (McKay et al., 1991). From the time of their first interactions with the lunar soil, the Apollo astronauts reported that it contained abundant small particles that had a strong tendency to collect on, adhere to, or otherwise contaminate, the surfaces of equipment used in extravehicular activity (EVA) operations. Apollo crews referred to these smaller particles as (lunar) “dust,” an informal term that is only now becoming more formally defined as lunar soil particles smaller than 10 to 20 μm in diameter (Greenberg et al., 2007).

Numerous references by the Apollo crews to the effects of lunar soil (both dust and larger particles) on a range of systems and crew activities during lunar surface operations occur within Apollo technical crew de-briefings and post-mission reports (Gaier, 2005; Wagner, 2006). As might be expected, among the EVA systems mentioned frequently by the crews in relation to possible lunar dust/soil effects were the model A7L and A7LB spacesuits worn during lunar surface operations. Based on a tabulation by Gaier (2005), approximately 25% of crew references to lunar dust effects in post-mission reports pertain to dust interactions with spacesuits. These include directly observed effects (e.g., dust adhering to spacesuit fab-

rics), as well as system and mechanism behaviors that were indirectly, and perhaps subjectively, interpreted to be due to dust (e.g., suit pressure decay and problems with fittings). Although Apollo-era post-mission disassembly and testing was conducted on selected lunar EVA spacesuit components, very few tests were designed to look specifically at dust effects, and no follow-on studies designed to do so have been conducted since Apollo. This is despite the fact that both the objective and subjective content in the Apollo crew and mission reports, as well as anecdotal evidence, have elevated spacesuit performance as a major issue in NASA's developing strategies for dealing with lunar dust effects during more extended lunar surface missions (Wagner, 2006).

This report summarizes the results of the first post-Apollo-era direct study of the effects of lunar soil, including particles in the dust size range, on the materials and mechanisms of selected A7L/A7LB flight-article spacesuits from the Apollo lunar surface missions. The study is the product of the NASA Smithsonian Dust Investigation Research Team (NASDIRT), a multi-disciplinary team that has brought together experts from both NASA and the Smithsonian Institution to perform a forensic post-flight analysis of dust effects on a set of 38-year-old spacesuits that now form part of a treasured national collection of historical space artifacts. The top-level goal of this work has been to expand, by direct engineering characterization and measurement, the base of current understanding of how these spacesuits performed in the lunar dust environment. Such engineering data are needed to support rapidly expanding efforts within NASA's Constellation Program and other organizations to define requirements for the next generation of lunar surface systems, which include spacesuits. Because the A7L/A7LB spacesuits represent the first integrated set of spacesuit materials, mechanisms and systems to be field tested in the lunar dust environment, the lessons learned from the performance of these spacesuit components are a key starting point in integrating dust mitigation and dust tolerance into the next generation of lunar spacesuits.

Project Objectives

Formulation of the NASDIRT Project objectives started from an initial recognition of a lack of engineering verification of many of the crew and mission reports on the effects of lunar dust on the Apollo spacesuits. Project objectives were then refined based on assessment of NASA's future needs and requirements in spacesuit development. Final objectives were established based on discussions with Smithsonian Air and Space Museum staff to determine which Apollo spacesuits could be made available for study, their overall condition, and the constraints on examining them based on Smithsonian curatorial guidelines.

Table 1 summarizes the project's specific technical objectives organized according to the spacesuit components and systems that were available for study. The objectives, and their associated data deliverables and study results, have the following relevant connections to NASA's current lunar exploration programs:

1. Characterization of physical abrasion/frictional wear of suit outer components (e.g., outer fabric) will help NASA determine whether any of the Apollo-era spacesuit materials and systems are candidates for use in future lunar EVA spacesuit systems. The performance or lack of performance of these materials and designs with respect to effects from lunar dust and/or larger soil particles provide a test basis for defining requirements for future spacesuit capabilities.
2. Determination of the lunar soil/dust contamination levels on A7L/A7LB spacesuits will define the overall dust loading expected for this particular spacesuit design, with application to requirements for future spacesuit designs.
3. Investigation of the size distribution and mineralogy of the contaminating particles will help determine the degree to which contamination is "selective" with respect to the size and type of particles that adhere to the suit. Overall, information on the amount, type and size of contaminating dust helps to describe the various risks that spacesuits pose for introducing dust from the lunar surface into the pressurized environment of a spacecraft or lunar habitat.

4. Investigation of possible dust contamination and associated mechanical wear effects for the A7LB spacesuit glove wrist disconnect rotating bearing provides data on how well this particular rotating pressure seal, combined with the other aspects of the glove design, performed with respect to preventing and/or withstanding dust's effects on the bearing mechanism. These results, in turn, help to determine whether the basic aspects of this rotating seal design are candidates for use in future designs for sliding/rotating pressure seals for use in various systems.
5. Investigation of lithium hydroxide (LiOH) canister filters from the Apollo Command Module (CM) provide information on the size and type of dust particles that ultimately ended up inside the respirable atmosphere of the CM after completion of the lunar surface mission. These data can ultimately be compared against crew health requirements for permissible levels of inhaled lunar dust to determine the overall health threat from inhaled dust during an Apollo-type reference mission.

Table 1. NASDIRT Project Technical Objectives

Technical Objective	A7L / A7LB Assemblies Studied for this Objective
1. Lunar soil/dust contamination-spacesuits: <ul style="list-style-type: none"> – Investigate variations in absolute and relative amount of residual lunar soil/dust particles on suit outer components – Assess, as far as possible, the mechanisms by which soil grains adhere to, or are embedded in, space suit outer fabrics and components. – Determine the size distribution, grain shape and mineralogy of grains adhering to suit outer components 	<ul style="list-style-type: none"> ▪ Outermost soft fabric coverings on <ul style="list-style-type: none"> – EV ITMG (spacesuit torso and limbs) – EV pressure glove outer materials
2. Characterize the nature and degree of <u>physical</u> abrasion/frictional wear experienced by suit outer components. <ul style="list-style-type: none"> – Differentiate/compare/contrast wear phenomenon caused by lunar soil/dust as opposed to other causes 	<ul style="list-style-type: none"> ▪ Outermost fabric and hard material coverings on: <ul style="list-style-type: none"> – EV ITMG (spacesuit torso and limbs) – EV Pressure Glove Assembly
3. Investigate effects from soil/dust introduction into sliding/rotating pressure seal assemblies <ul style="list-style-type: none"> – Characterize nature and degree of physical abrasion/frictional wear and assess role of soil particles in causing wear. – Assess presence of soil particles in assemblies as indication of soil penetration past pressure seals. – Determine size distribution and mineralogy of any soil/dust grains found in seal assemblies. 	<ul style="list-style-type: none"> ▪ EV Pressure Glove Assembly – Glove Wrist Disconnect Rotating Bearing ▪ IV Pressure Glove Assembly – Glove Side Wrist Disconnect Rotating Bearing
4. Lunar soil/dust contamination-spacecraft <ul style="list-style-type: none"> – Determine amount, size distribution and mineralogy of lunar dust/soil particles in air filter materials within Command Module lithium hydroxide (LiOH) CO₂ scrubber canisters. 	Spacecraft assemblies studied: <ul style="list-style-type: none"> ▪ Command Module LiOH canister filters

Background

Apollo Spacesuit Design and Construction

The Apollo spacesuits had several design variants depending on their application during a mission, and on the stage in the Apollo program in which they were developed. A comprehensive summary of these design variants, with technical details, is provided by Lutz et al. (1975). One main difference in suit configuration was between the A7L and A7LB designs used earlier and later in the program, respectively. Another important difference was between the intravehicular or IV suit worn by the command module pilot (CMP), and the extravehicular or EV suit worn by the mission commander (CDR) and lunar module pilot (LMP). The following summary focuses principally on the EV suit, with differences relative to the IV spacesuit being noted as appropriate.

During EVAs on the lunar surface, Apollo crew members wore an integrated extravehicular mobility unit (EMU) consisting of a pressure garment assembly or PGA (the space “suit” itself) that was connected to a two-system backpack comprised of a larger portable life-support system (PLSS), and a smaller oxygen purge system (OPS). The PGA is an air-tight anthropomorphic structure comprised of the following main assemblies:

1. An inner multi-layer protective envelope garment called the torso limb suit assembly (TLSA) that has integrated pressure boots and contains attachment fittings for a pressure helmet and gloves.
2. A pressure helmet assembly that attaches directly to fittings on the TLSA
3. Pressure gloves, of either intravehicular (IV) or extravehicular (EV) type, that attach directly to the TLSA.
4. An outer multi-layer protective garment called the integrated thermal micrometeoroid garment (ITMG) that conforms over the TLSA except for the head and hands and which includes an additional upper boot covering
5. A lunar boot that provides thermal and abrasive protection for the TLSA pressure boots during lunar surface operations

The TLSA with attached pressure helmet and gloves comprises the pressure suit portion of the PGA, with protection from abrasion, and the lunar thermal and micrometeorite environment being provided by the ITMG, the EV-type pressure glove and the lunar boots. These three latter assemblies were the principle focus of the current study, together with the wrist bearing mechanisms of the EV and IV pressure gloves. The specific differences between the IV and EV pressure glove assemblies are described further below.

There were two different configurations of the space suit assembly used between the earlier and later Apollo lunar surface missions. The A7L PGA model was used on Apollo 11 to Apollo 14 and the A7LB PGA model supported Apollo 15 to Apollo 17. The A7LB configuration resulted as a redesign of the A7L PGA that required incorporation of design enhancements based on additional requirements that included an increase in the number of lunar surface EVA periods to three and an increase in the time of each EVA to eight hours. In addition, the lunar rover vehicle (LRV) became available for these missions, which added the requirement for waist mobility to enable astronauts to get on, drive, and get off the LRV. Incorporation of a waist convolute into the A7LB PGA for waist mobility precluded the use of the A7L-type rear vertical entry closure zipper arrangement. As a result, a new entry zipper closure system was developed that extended from the upper right front side near the torso/neck interface to under the right arm, passing diagonally across the back, and ending at the lower left front side. Other changes incorporated in the A7LB PGA included an increase in the diameter of the glove wrist disconnects to provide for easier donning and greater wrist comfort. Improvements were also made to the ITMG to improve its abrasion resistance.

Study Materials

Spacesuit Selection

A list of the Apollo spacesuits and associated sub-assemblies studied as part of the NASDIRT Project is provided in Table 2. Through agreements between NASA and the Smithsonian Institution, the Smithsonian National Air and Space Museum (NASM) made available a limited number of Apollo flight article spacesuits and their sub-assemblies for the current study. The two main factors in selecting particular spacesuits for study were Smithsonian curatorial and historical preservation requirements and the availability of spacesuits that had not been extensively cleaned after the mission. The curatorial requirements precluded any disassembly or sampling of PGA systems and components that could be judged to be destructive, and excluded certain space suits from study that were of particular historical importance (e.g., the Apollo 11 spacesuits). The fact that the majority of the Apollo spacesuits had undergone disassembly, cleaning, and reassembly immediately after their missions reduced their usefulness for project objectives related to determining levels of dust contamination.

Table 2. Apollo spacesuits studied

Mission	Worn by Crew Member (Role)	Spacesuit Model	Subassemblies Studied	Notes/Serial Numbers
Apollo 12	Alan Bean (LMP)	A7L	ITMG outer materials	P/N A7L-201100-28 S/N 077; Model # 2001A
Apollo 16	Charles “Charlie” Duke (LMP)	A7LB	EV pressure glove	Left, NASM 3037, 1974-0150-002
			IV pressure glove	Left, NASM 3037, 1974-0150-004
Apollo 17	Harrison H. “Jack” Schmitt (LMP)	A7LB	ITMG outer materials	Studied as part of integrated PGA
			EV pressure glove	Right, NASM 3048 1974-0183-006
			EV pressure glove	Left, NASM 3048, 1974-0183-005

After review, the model A7LB spacesuit worn by Apollo 17 lunar module pilot (LMP) Harrison H. “Jack” Schmitt was identified as a prime study candidate because its ITMG had a “dirty” appearance that suggested the presence of a significant amount of lunar soil contamination. Video footage taken during the Apollo missions shows that Schmitt had fallen or made contact with the lunar surface on more occasions than any of the other Apollo astronauts. The Smithsonian staff believed the latent soil was present because the spacesuit had bypassed normal post-mission disassembly and cleaning procedures. This spacesuit, including its pressure gloves and lunar boots, was allocated for study objectives that could be accomplished by non-destructive means and without disassembly. To support the project’s objectives related to sliding/rotating pressure seal assemblies (Table 1), the Smithsonian allocated the IV and EV pressure gloves worn by LMP Charlie Duke on Apollo 16, and authorized non-destructive disassembly, characterization and re-assembly of their respective glove-side wrist disconnect rotation bearings.

A third flight-article spacesuit worn on the lunar surface by Apollo 12 LMP Alan Bean was taken from collections within the Crew and Thermal Systems Division at NASA Johnson Space Center (JSC). The ITMG from this spacesuit had been cleaned and removed at NASA’s Manned Spacecraft Center (now JSC) after return from the Apollo lunar mission and subsequently sent to the White Sands Test Facility (WSTF) for examination of the mylar multi-insulation layup material. Although not specifically designed to look at lunar dust effects on the spacesuit materials themselves, these tests did obtain prelimi-

nary data on the number and size distribution of lunar soil particles adhering to the spacesuit fabric layers and other components. Results of the WSTF test activities are detailed in WSTF reports White Sands TRL-169-001, and TRL-169-003, authored by I.D. Smith (Smith, 1970a,b). Upon return from WSTF, the ITMG was bagged and retained in storage in the Crew and Thermal Systems Division at JSC until its use for the present study.

Spacesuit Operational and Post-Flight History

Although the Apollo missions carried only one set of spacesuits, not all components and sub-assemblies of a given spacesuit had the same duration of use and history of wear. Some components were used both on the Moon and for limited periods inside the spacecraft. Others were used only on the Moon. For example, the integrated TLISA-ITMG portion of the spacesuit PGA worn on the Moon by the mission commander (CDR) and LMP was also worn during phases of intravehicular (IV) operation such as launch when there was increased risk of cabin de-pressurization. However, the crew wore glove and boot configurations on the lunar surface that were different from those worn for IV operations. The IV glove consisted of pressure bladder material molded to the wearer's hand. For lunar EV operation, a second glove was provided, consisting of a second IV glove covered by a multi-layered EV glove shell, the entire assembly being called the EV pressure glove. Likewise, for IV operation the CDR and LMP wore a two-assembly boot consisting of an inner TLISA pressure boot covered by a second boot assembly integrated with the ITMG (visible in photo of Apollo 12 ITMG in Figure 5 below). This two-assembly boot was in turn covered by a lunar boot used only for EVA on the lunar surface.

The NASDIRT team reconstructed operational timelines for the Apollo spacesuit components investigated in the current study from the transcribed recordings of the original Apollo mission audio transmissions as provided in the Apollo Lunar Surface Journal (Jones et al., 2006) and the Apollo Flight Journal (Woods et al., 2006). Because there is currently no publicly available Flight Journal for Apollo 17, the timeline for the Apollo 17 LMP spacesuit components covering the periods before and after lunar surface operations was reconstructed using the original nominal Apollo 17 mission flight plan, which included a nominal spacesuit usage history (Holloway, 1972). The data for these portions of the flight should therefore be regarded as estimates only.

A summary of the spacesuit component operational wear periods based on the reconstructed timelines is provided in Table 3. Periods of time that a given component was worn by the astronauts during both intravehicular activity (IVA) and each separate lunar surface EVA are listed against a basic mission timeline (Table 3). EVA wear periods are based on best indications from audio transcripts of the time a given component spent outside the Lunar Module (LM). These periods generally differ from official EVA recorded times, which are based on mission elapsed time (MET) for de-pressurization and re-pressurization of the LM. Wear periods for the Apollo 17 LMP EV pressure gloves and lunar boot during the individual EVAs are identical to that of the ITMG, so only the total wear time for these components are given.

Some basic features of the Table 3 data are worth noting. Both of the ITMG's investigated in the current study had periods of IV wear that significantly exceeded their wear periods on the lunar surface. For the Apollo 12 ITMG, in particular, this included an extended period of IV wear inside the LM while it was on the lunar surface, because the Apollo 12 crew never removed their PGA's from the time the LM undocked from the Command Module (CM) to the time it returned from the lunar surface. In contrast, the Apollo 16 and 17 crews removed their PGA's during rest periods between EVAs. Although crews generally tried to minimize the time the rather uncomfortable EV pressure gloves were worn inside the LM, the IV wear time for the EV pressure gloves was still significant because of periods the fully-suited LMP spent waiting for the mission CDR to exit the LM, and on final preparations before LM egress. Overall, the significant periods of time the spacesuit ITMG assemblies were worn inside both the LM and CM suggests that this time period should not be ignored in assessing overall wear and abrasion performance of the spacesuit outer materials.

Beyond the total duration of EVA wear for the spacesuit components investigated, further details on their EVA operational history, including effects of lunar dust noted by crew members, can be found in the

Apollo Lunar Surface Journal (Jones et al., 2006) and in the compilation by Gaier (2005). It is notable that the Apollo 17 PGA had over twice the EVA exposure time compared to the Apollo 12 spacesuit. Aspects of its operational history, such as a significant number of astronaut slips and falls, likely resulted in the Apollo 17 LMP suit accumulating a higher level of lunar dust contamination than other Apollo spacesuits.

Table 3. Mission wear history for Apollo spacesuit components

	Launch (hrs)	Trans-Lunar Insertion and Coast (hrs)	LM Undock, Lunar Descent, Landing, Surface Operations (hrs)	Lunar Ascent, Docking, LM Undocking (hrs)	Trans-Earth Insertion and Coast (hrs)	Re-entry and Re- covery (hrs)	Total (hrs)
APOLLO 12, ALAN BEAN, LMP, A7L ITMG							49.6
IV Wear	6.5		25.0	12.0			37.0
EVA 1 Wear			3.0				3.0
EVA 2 Wear			3.3				3.3
EVA Total			6.3				6.3
APOLLO 16, CHARLES DUKE, LMP, A7LB IVA PRESSURE GLOVE							20.8
IV Wear	6.07		12.6	5.6	2.6		20.8
EVA Wear							0.0
APOLLO 16, CHARLES DUKE, LMP, A7LB EVA PRESSURE GLOVE							43.8
IV Wear			5.2				5.2
EVA 1 Wear			6.6				6.6
EVA 2 Wear			7.4				7.4
EVA 3 Wear			5.3				5.3
EVA Total			19.3				19.3
APOLLO 17, SCHMITT, LMP, A7LB ITMG							80.4
IV Wear	6.5		29.5		3.0		39.0
EVA 1 Wear			6.7				6.7
EVA 2 Wear			7.2				7.2
EVA 3 Wear			6.8				6.8
EVA Total			20.7				20.7
APOLLO 17, SCHMITT, LMP, A7LB, EV PRESSURE GLOVE ASSEMBLY							22.8
IV Wear			2				2.0
EVA Total			20.8				20.8
APOLLO 17, SCHMITT, LMP, A7LB, LUNAR BOOT							37.8
IV Wear			17				17.0
EVA Total			20.8				20.8

A short summary of the geological differences between the areas of EVA operations for the Apollo 12, 16 and 17 landing sites is provided by Spudis and Pieters (1991), and details on the mineralogical and compositional differences between the lunar soil at these sites is discussed by McKay et al. (1991). Apollo 12 landed on an area of the lunar mare in southeastern Oceanus Procellarum where the soils are derived primarily from mare basalts (McKay et al., 1991; McKay et al., 1971). Apollo 16 explored the central lunar highlands near Descartes Crater where the soils reflect the feldspar-rich mineralogy of impact rocks derived from the lunar highlands (Spudis and Pieters, 1991; McKay et al., 1991). The Apollo 17 EVAs occurred in a mare-highland boundary area of the Taurus-Littrow valley where soils

with both mare and highland characteristics occur (Spudis and Pieters, 1991; McKay et al., 1991; Taylor et al., 2001).

Based largely on Smithsonian records, the post-flight histories of the Apollo 12, 16 and 17 spacesuits are known to be substantially different. Documentation regarding details of these histories, including NASA records on chain of custody, was not easily obtainable, and a thorough search for these records was judged to be beyond the scope of the present investigation. The available information on post-flight history revealed that the Apollo 12 LMP ITMG was subjected to a post-flight analysis at WSTF approximately six weeks after the end of the mission. Subsequent to this analysis, custody was given to the Crew and Thermal Systems Branch at NASA Johnson Space Center where the ITMG has remained in bagged storage. For the Apollo 16 spacesuits, documentation from ILC Industries (Lirado, 1972), shows that the spacesuits underwent extensive post-flight inspection, testing and cleaning at ILC facilities approximately four months after the mission. This work included selected tests and evaluation of the LMP EV and IV pressure gloves investigated in the current study. Subsequent to the ILC evaluation, the Apollo 16 spacesuit was transferred to the Smithsonian NASM through NASA and accessioned into the museum collections in 1974. The EV and IV pressure gloves then immediately went on loan to the U.S. Space and Rocket Center (USSRC) in Huntsville, Ala. After 10 years on loan to the USSRC the gloves were sent to the South Carolina State Museum where they remained until 1999 when they were returned to the NASM. The history of the Apollo 17 LMP spacesuit worn by Harrison H. Schmitt consisted of transfer to the NASM from NASA in 1974, followed by immediate loan to the Adler Planetarium in Chicago for one year, followed by direct transfer to the Roswell Museum in New Mexico, until it was returned to the NASM in 1999. As noted above, there is reason to believe this spacesuit bypassed the post-flight cleaning and testing procedures that ILC performed on the Apollo 16 and other Apollo spacesuits.

Apollo Command Module LiOH Canister Filters

Air quality and CO₂ levels were maintained in the Apollo command modules using LiOH canisters. There were 30 canisters on each mission (Fig. 1), which were installed in pairs and changed every 12 hours. The NASDIRT project carried out an extensive search to locate the canisters from the missions, but ascertained that few survive. It seems likely that most were simply discarded at the end of the missions. One relatively complete set from Apollo 11 was located in the collections of the Smithsonian NASM and a single canister was located from Apollo 17 at JSC. Documentation giving the time of installation of each canister was available (Fig. 2), allowing three canisters (Nos. 9, 10, 11) to be selected that were installed at the time the hatch was opened as the LM docked with the CM in lunar orbit on the return journey to earth.

The canisters consist of LiOH in dry solid form and at the back of each canister a thin layer of activated carbon in a lightweight aluminum container. The intake side of the canisters included a relatively coarse Nomex® (E. I. du Pont de Nemours and Company) filter behind a wire grill, the main purpose of which was to keep the contents of the canister in place. Circulating air was split such that a percentage of the air flowed through the filter (and the LiOH), while the remaining air bypassed the filter through a central core. Lunar dust was thus potentially trapped on the outer surface of the Nomex® filter before the air passed through the LiOH.

Methods and Procedures

Curation Requirements and Analysis Constraints

The Apollo spacesuits are national heritage items that are becoming fragile with time as the polymers and other materials used in their construction deteriorate. Consequently, for the Apollo spacesuit components obtained from the Smithsonian collections, the characterization methods used in the current study were subject to certain constraints arising from museum conservation and curation requirements. Because

the Apollo 12 spacesuit components had been previously retained by NASA for destructive analysis, there was more flexibility in the methods used to sample and characterize these particular materials. For the Smithsonian items, the requirements limited disassembly of spacesuit components to only those actions that could be demonstrated to be substantially reversible, with no loss of essential material, introduction of foreign components, or associated physical damage. Any sampling of material from the spacesuits, or characterization of spacesuit components *in-situ* or in a partly disassembled state, had to be approved in

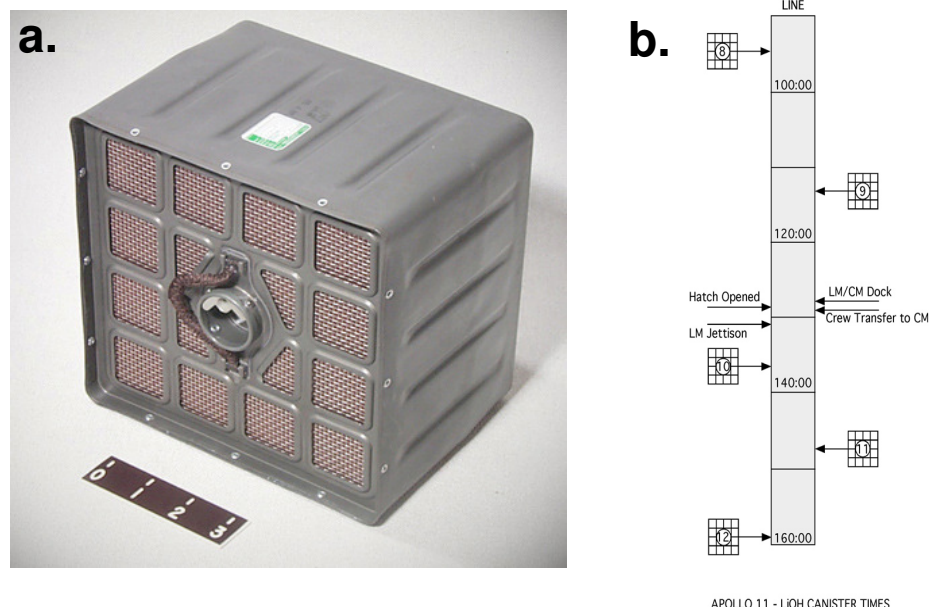


Figure 1. (a) Intake side of an Apollo lithium hydroxide (LiOH) canister. The Nomex filter lies immediately behind the wire grill that protects the air intake. (b) Portion of the Apollo 11 mission timeline showing Mission Elapsed Time (MET) at which LiOH canisters were replaced.

the context of these requirements. For the Smithsonian Apollo 16 and Apollo 17 spacesuits the following direct characterization methods were approved:

1. Extraction and characterization of particulates from the outer surfaces of the Apollo 17 ITMG using an adhesive tape “pull” technique. As described below, this technique was tested and found to extract particles from surfaces without damaging the sampled surface or leaving a residue that chemical or optical tests could detect.
2. Optical binocular stereomicroscope observation of the outer surfaces and components of the Apollo 17 integrated ITMG and lunar boot with no disassembly.
3. Optical binocular stereomicroscope observation of all surfaces of the Apollo pressure gloves that were accessible without disassembly.
4. Observation of the outer surfaces of the Apollo 17 EV pressure glove outer materials assembly in a large-chamber scanning electron microscope (SEM), provided no conductive coatings were applied and no disassembly was performed.
5. Optical and SEM examination of the inner ball bearing race surfaces of the 360° rotation bearing in the male half of the Apollo 16 EV and IV pressure gloves. This examination required disassembly, cleaning and reassembly of the sealed rotation bearing, which was approved on the basis of having a low risk of causing damage.
6. Chemical analysis of the surface of the ITMG outer fabric using a portable energy-dispersive X-ray fluorescence spectrometer. This technique involved a small amount of contact pressure on the

fabric by the spectrometer sensor and exposure of the suit materials to low-energy X-rays that were judged to not be harmful.

For the Apollo 12 spacesuit, there were fewer restrictions on physical sampling of the suit materials because the spacesuit had previously been allocated for studies involving disassembly and some destructive testing. Therefore, in addition to performing non-destructive tests and sampling that mirrored those performed on the Apollo 17 suit, it was possible to physically remove suit materials, specifically samples of ITMG fabric, for detailed study by multiple techniques. Fabric swatches 4-6 cm² in size were obtained from a highly worn and very dirty area on the ITMG left knee and from a relatively pristine area that was partially covered under a U.S. flag patch during the mission.

The Apollo 11 LiOH canisters obtained from the Smithsonian NASM were approved for a study method that involved disassembly of the filter to reveal the Nomex filter, rinsing the filter with ethyl alcohol to collect trapped particulates, followed by reassembly. This procedure was considered to be minimally invasive and acceptable under Smithsonian guidelines.

Tape Extraction of Surface Particulates

For reasons outlined above, it was necessary to develop techniques for sampling particulates from the surfaces of suit materials, particularly the outer woven Teflon® (E.I. du Pont de Nemours and Company) fabric layers, which minimized the potential for physical damage or chemical contamination. A simple technique using adhesive tape (3M Company's Scotch® Magic or other similar product) to "pull" particles off a surface of interest was developed. Initial experiments were carried out using pristine remnant pieces of original Apollo suit fabric and lunar soil simulant (JSC1af, Hill et al., 2007). Soil simulant was ground into the fabric. The fabric was then cleaned by vigorous brushing and adhesive tape briefly applied to the selected site on the fabric surface. The tape was then immediately peeled off and attached face down on waxed paper for storage. In the laboratory, the adhesive tape was peeled from the waxed paper and coated with conducting evaporated carbon for SEM examination. Comparative SEM examination of the fabric before and after tape sampling, and the surface of the tape itself, indicated the tape extracted approximately 70% of latent particles from the fabric surface. Subsequent Fourier Transform Infrared microscopy examination of the fabric and other spacesuit materials revealed that the tape left negligible adhesive residue on the sampled surface. On the latter basis the tape sampling method was judged to be sufficiently non-destructive to meet Smithsonian curation criteria

Optical Microscopy Techniques

In the current study, optical microscopy performed with binocular stereomicroscopes was a key tool, particularly for examining the surfaces of larger parts and assemblies. The use of stereomicroscopes, as opposed to higher magnification compound microscopes, was necessitated by the size and bulk of most objects investigated, and by restrictions on extracting physical samples that would fit under the shorter working distance of a compound microscope. Stereomicroscopy with digital microphotography was performed both at the Smithsonian Institution Museum Conservation Institute (MCI) using a Wild Company Model 5a stereomicroscope and at NASA JSC using Nikon corporation's model SMZ 1500 stereomicroscope. The MCI stereomicroscope was used principally for examination of the outer surface of the Apollo 17 spacesuit ITMG surface, and was fitted on a larger arm mobile support for this purpose. Figure 2 shows a typical highest-magnification digital image of a swatch of the ITMG outermost T-164 Teflon fabric containing areas of lunar soil contamination. As Figure 2 shows, under these imaging conditions it is generally possible to resolve particles 5-10 µm in diameter as long as they are significantly darker than the background fabric.

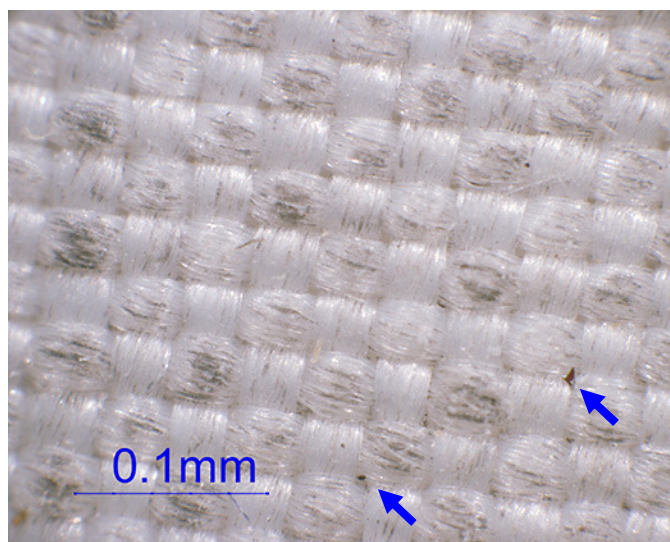


Figure 2. Light-optical stereomicroscope image showing typical resolving power for imaging of Apollo spacesuit T-164 Teflon outer fabric. Arrows show dark particles that are probably lunar soil grains.

Scanning Electron Microscopy Techniques

Imaging and chemical microanalysis with a scanning electron microscope (SEM) was the principal technique used for the characterization of particle samples extracted from spacesuit surfaces using adhesive tape, as well as those rinsed from the LiOH canister filters. Other spacesuit materials and component examined by SEM methods include: 1) outer fabric swatches from the Apollo 12 ITMG, 2) the outer surface of an intact Apollo 17 EV pressure glove, 3) surfaces on the inner ball bearing race from rotation bearings for the Apollo 16 EV and IV pressure gloves.

SEM examination of the adhesive tape particle samples and the pressure glove rotation bearings was performed at NASA JSC using a JEOL 5910LV scanning electron microscope equipped with an iXRF energy dispersive X-ray spectrometer (EDS). The Apollo 12 fabric swatches were studied at NASA Glenn Research Center using Hitachi Company's model S4700II Field-Emission SEM.

Surface examination of the intact Apollo 17 EV pressure glove was performed at the Smithsonian Institution Museum Conservation Institute using a Hitachi Company's model S-3700 SEM. This SEM had a sample chamber large enough to accept an entire EV pressure glove without any disassembly. Additional details on the sample preparation and imaging techniques used for the various samples and materials examined by SEM are listed in the relevant sections below.

X-ray Fluorescence Spectroscopy

At the Smithsonian Museum Conservation Institute, a portable energy-dispersive X-ray fluorescence (ED-XRF) spectrometer was evaluated as a means to measure surface-correlated variations in the chemical composition of the outer fabric of the Apollo 17 LMP ITMG and lunar boot. The goal was to determine if chemical compositions measured by ED-XRF spectroscopy could be tied to levels of lunar soil contamination. The instrument used in this analysis was an Innov-X Systems® Alpha Series™ (Innov-X Systems, Inc.) model XT-440 handheld energy dispersive X-ray fluorescence spectrometer (Fig. 3). The spectrometer generates a primary 15 or 35 keV X-ray beam that excites secondary X-rays from chemical elements of interest in the analyzed target material. Analytical sensitivity of the Innov-X Systems ED-XRF is negligible for elements with atomic numbers lower than 14 (elements P and below), and therefore the major lunar soil elements Mg, Al, and Si could not be detected. However, through the use of specific



Figure 3. Innov-X Systems portable energy-dispersive X-ray fluorescence (ED-XRF) spectrometer (blue unit) held in positioning tripod for chemical analysis of outer fabric of Apollo 17 spacesuit..

pre-set analytical modes, sensitivity for analyzable elements could be adjusted to yield good detection for the lunar soil major elements Ca, Ti and Fe. The two pre-set analytical modes determined to be the most useful were “soil mode”, which uses a 35 keV primary beam, high X-ray tube current, and Al filter to analyze elements with secondary X-ray energies in the 3.5 – 30 keV range, and the “Light Element Analysis Program (LEAP)”, which uses a 15 keV primary beam, high X-ray tube current, and Al filter to optimize for energies between 2.0 to 7.5 keV.

The secondary X-ray intensities for analyzed elements are counted by the spectrometer using a solid-state silicon PN diode detector, and element concentrations are generated by the Innov-X Systems software from the intensities using empirical, linear calibration factors derived from external standards. The primary beam spot size of about 1.4 cm in diameter and the depth of penetration of the primary beam determine the analyzed volume in the target material. The depth of penetration varies considerably, depending on the beam settings, the material density and atomic numbers of the elements present, and the loss of photons from scattering in air and/or through the analyzed material itself. For the current application, the depth of penetration of a 35 kV and 13 microA X-ray beam (i.e., “soil” mode settings) in a light element matrix is expected to be on the order of 1-2 cm. Use of a brass foil inside a sleeve of the spacesuit showed that X-ray penetration with these settings exceeded the layered fabric thickness, although copper secondary X-ray intensities were greatly attenuated. Therefore, the depth of penetration of the X-ray beam at the lower power of 15 kV and 12 microA (“LEAP” mode) was expected to approximate the fabric thickness. For each analysis point on the spacesuit, readings were taken sequentially in the soil mode followed by LEAP mode, with 90-second total count times each.

Although the ED-XRF spectroscopy unit is capable of acquiring data while being hand-held it was possible, for the current application, to mount the unit on a specially designed tripod and still reach all analysis locations on the ITMG outer fabric and lunar boot that were of interest (Fig. 3). The stationary tripod allowed for optimum positioning of the detector relative to spacesuit fabric surface, and permitted longer counting times thereby increasing the peak-to-background ratio.

Although both the soil and LEAP modes have good detection limits for Ca, Ti and Fe, there were several factors, such as the uncertain analytical geometry, the properties of the target, and heterogeneous layered material matrix, which limited implementation of ED-XRF spectroscopy as a fully quantitative analytical technique. On the semi-quantitative comparative level, the ED-XRF spectroscopy results were nevertheless useful, and are discussed in detail below.

ITMG Outer Materials Results

ITMG Materials and Construction

The ITMG (integrated thermal micrometeorite garment) is a multi-layer protective garment that covers the spacesuit torso limb suit assembly (TLSA). It functions effectively as a multipurpose shell that conforms over the contours of the TLSA, the latter functioning, together with helmet, gloves and boots, as the pressure suit portion of the spacesuit. The ITMG itself is designed to provide protection against the thermal and micrometeorite hazards encountered on the lunar surface as well as resistance to potential flame in the spacecraft environment. In addition, because the ITMG comprises the outermost part of the spacesuit, it also provides a number of functional capabilities in the form of pockets and belt loops for equipment storage and attachment, and access flaps that cover the entrance closure, life-support hose connector and biomedical injection area. As a result, the outermost surface of the ITMG has a complex geometry of fabric and metal subcomponents that include fittings, seams, fasteners and closures that provide a variety of sites for potential adhesion and retention of lunar dust particles. The basic ITMG multi-laminate fabric assembly itself is comprised of five to six different types of material which are diagrammed and described after Lutz et al. (1975) in Table 4. In the current investigation, direct characterizational work, including particle sampling and microscopic imaging, was restricted to only the outermost fabric layers, specifically the 1a-Teflon T-164 fabric used on high-abrasion areas (Table 4), and the 1b Teflon-coated fiberglass 4484 “beta cloth” that comprised the outermost fabric on most other areas of the suit (Table 4). This restriction arose from curatorial constraints that did not permit disassembly of the fabric layup of the Apollo 17 LMP suit, and from sample availability and time constraints for the Apollo 12 LMP suit. The T-164 teflon and 4484 beta cloth were both used in plain weave and “twill” weave varieties in the Apollo spacesuits, with the less abrasion-resistant twill weave used in spacesuits on earlier missions (Fig. 4). Beta cloth was originally developed under contract to NASA by the Owens Corning Fiberglass Corporation in Ashton, Rhode Island. Additional details on beta cloth and related high performance fabrics used by NASA are discussed by McQuaid et al. (2005).

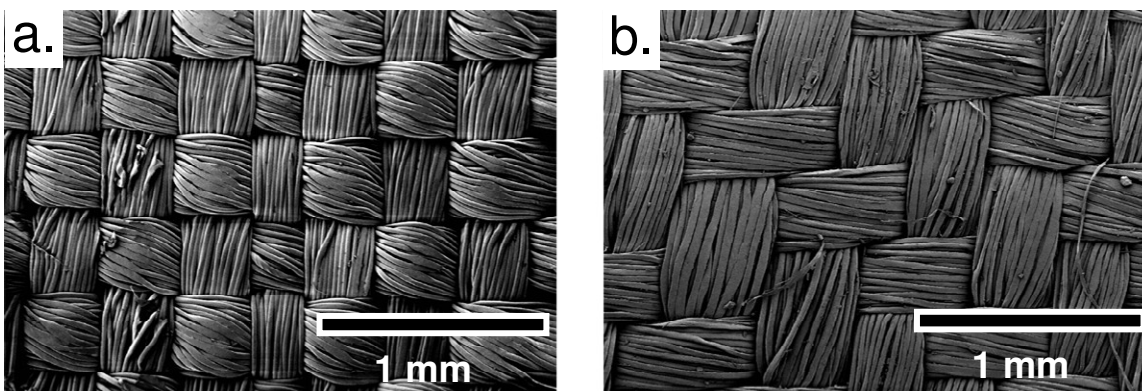


Figure 4. SEM secondary electron images of outermost T-164 Teflon fabric showing examples of both plain weave (a) and twill or diagonal weave varieties (b).

Table 4. Material sequence cross-section for ITMG fabric assembly (modified from Lutz et al., 1975)

Layer Sequence (relative to surface)	Material	1 st -Level Function	2 nd -Level Function	Description
1a	Teflon cloth (T-164 8.5 oz woven Teflon fabric)	Abrasion resistance	Flame resis- tance	Used for extra abra- sion resistance on selected areas: knee, waist, elbow and shoulder
1b	Teflon-coated filament beta Cloth (beta 4484)	Flame resistance	Abrasion resis- tance	Provides continuous outer fabric flame and abrasion resistance
2	Aluminized Kapton film/beta marquisette* laminate	Thermal radiation protection	Thermal cross section	Provides thermal and micrometeoroid pro- tection
3	Aluminize Mylar	Thermal radiation protection		
4	Non-woven Dacron	Thermal Spacer Layer		Provides thermal pro- tection
Repeat 3				
Repeat 4				
Repeat 3				
Repeat 4				
Repeat 3				
Repeat 4				
Repeat 3				
Repeat 2				
5	Rubber-coated nylon (ripstop)	Inner liner	Contact layer with the TLSA	

*see McQuaid et al. (2005)

Apollo 12 LMP Alan Bean

Previous Results

Of all of the spacesuits worn on the Moon, only the spacesuit worn by the Apollo 12 LMP Alan Bean was permanently disassembled for the purpose of post-flight analysis. This analysis was conducted at the Test Operations Office at NASA's White Sands Test Facility (WSTF) shortly after the flight as documented in NASA Technical Reports Nos. TR-169-001 and TR-169-003 (Smith, 1970a, b). An image of the ITMG portion of the spacesuit taken as part of the White Sands analysis is shown in Figure 5.

The WSTF study included an investigation of the size distributions and relative total amounts of lunar dust particles adhering to, and contained within, various components from the Apollo 12 spacesuit and spacecraft. This included work to establish the size distribution and relative total amounts of dust held on or within the various layers of ITMG fabric (see TR-169-003, Smith, 1970b). Results were obtained for fabric layers over the left knee cap, which included the outermost Teflon T-164 cloth abrasion patch at this location (Layer 1a, Table 4), and for layers located on the leg below the left knee where beta cloth



Figure 5. Integrated thermal micrometeorite garment (ITMG) from model A7L spacesuit worn on the lunar surface by Apollo 12 LMP Alan Bean. Image originally appeared in NASA Technical Report TR 169-001 prepared at the White Sands Test Facility.

(Layer 1b, Table 4) is the outermost layer. At these locations particle concentrations and size distributions were measured on both the outer and inner surfaces of the 1a -Teflon and 1b-beta cloth layers, and on the outer surface of the aluminized Kapton® (E.I. du Pont de Nemours and Company) layer (Layer 2, Table 4). The overall findings were that, while lunar dust particles did penetrate the weaves of the 1a-Teflon 164 and 1b-beta cloth fabric layers to slightly contaminate the layer 2 Kapton, the amount was not judged to be significant. In general, the concentration of particles was observed to fall off rapidly between the outer and inner surfaces of the 1a-Teflon 164 first layer, with the second 1b-beta cloth layer working to further reduce the amount of particulate penetration, particularly for particles less than 10 μm in size.

Fabric Analysis

The White Sands analysis focused primarily on dust contamination within the ITMG fabric layers and only did a limited study of wear and degradation of the fabrics themselves. Analysis was limited to what could be learned from optical microscopy with some limited application of the electron probe microanalyzer (EPMA). To gain a greater understanding of the effect of lunar dust on the condition of the fabric, the current study used SEM techniques to investigate three samples of the ITMG outer fabric. The samples consisted of fabric swatches 4-6 cm^2 in size obtained from a highly worn and very dirty area directly on the ITMG left knee, and from an area on the left shoulder that was partially covered under a U.S. flag patch (Fig. 6). Although it is a single piece of fabric, the flag patch swatch was treated as two fabric samples; the covered portion representing unexposed material and the uncovered portion represented exposed material. Thermal analysis confirmed that all fabric samples consisted of pieces of the supplemental 1a-layer of T-164 Teflon abrasion fabric that was added to the shoulder and knee areas of the A7L spacesuits (see Table 4).

A series of SEM secondary electron images of the T-164 Teflon fabric from the left knee area are shown in Figure 7. Note that the fabric has a twill or diagonal-type weave pattern that is distinct from the plain weave that is more prevalent on the outer fabrics used on later Apollo spacesuits. In general, twill weaves are less durable than plain weave fabrics. In lower magnification images (Fig. 7), the fabric fiber bundles appear to be relatively intact. However, at higher magnifications (Fig. 7), lunar soil particles are



Figure 6. Samples of outer fabric from Apollo 12 LMP spacesuit. (a) Outer surface of T-164 Teflon outer abrasion fabric from left knee, (b) T-164 Teflon fabric swatch from left shoulder; lighter area was covered under U.S. flag patch. (c) Comparative size of swatches shown in (a) and (b).

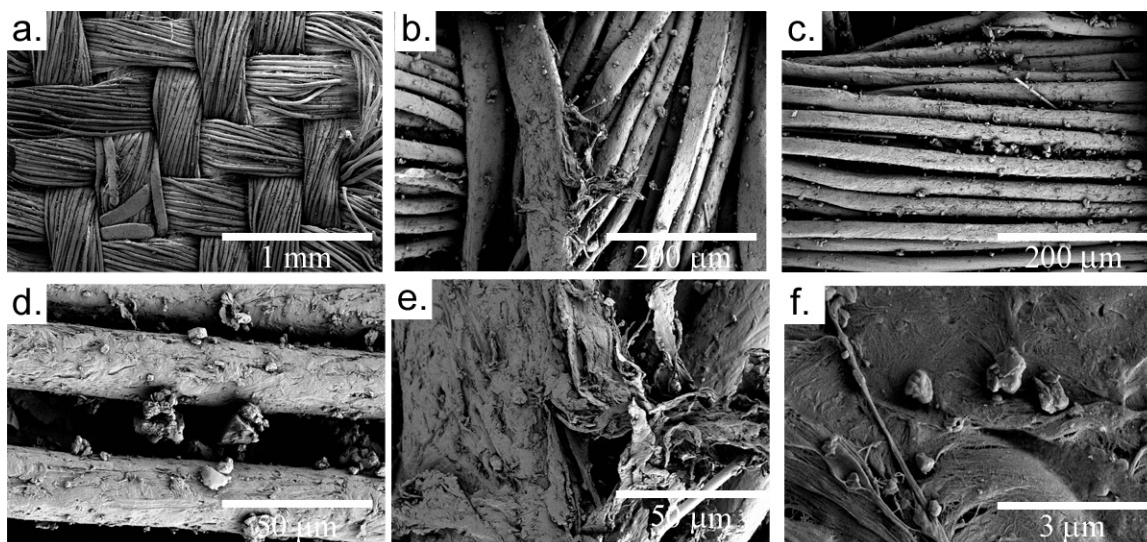


Figure 7. SEM secondary electron images of T-164 Teflon from left knee area of Apollo 12 LMP ITMG.

visible in-between the fibers and individual fibers show some crazing and fraying of the Teflon material. In places, it appears that soil particles have pushed fibers apart and caused individual fibers to fray, although no fibers appear to be completely broken. At the highest magnification, particles are visible embedded between fiber strands. Additional SEM secondary electron images in Figure 8 show stick-shaped particles of fiberglass present on the fabric. These particles are likely derived from highly abraded beta cloth fibers on adjacent or underlying areas of the ITMG.

Secondary electron images of the unexposed and exposed fabric areas from the left shoulder are shown in Figures 9 and 10 respectively. The unexposed area underneath the flag patch exhibits very little wear and tear, but a number of lunar soil grains are present on and between the fibers (Fig. 9). The latter observation indicates that some degree of soil particle penetration through the patch fabric or the sewn edge was possible, or alternatively, that particles were able to move to the outer fabric surface from contaminated areas inside the suit. The exposed fabric shows significantly more wear relative to the adjacent unexposed area (Fig. 10), but overall, it is less than the wear observed for the knee area (Fig. 7).

A summary of the representative levels of wear and abrasion observed for the fibers comprising the three fabric areas studied is shown in Figure 11. The ability of lunar soil to produce these and the other observed wear features was studied in a controlled abrasion test. The objective was to verify that lunar soil interaction, as opposed to wear caused by contact with hard surfaces (e.g., LM ladder, LM hatch and

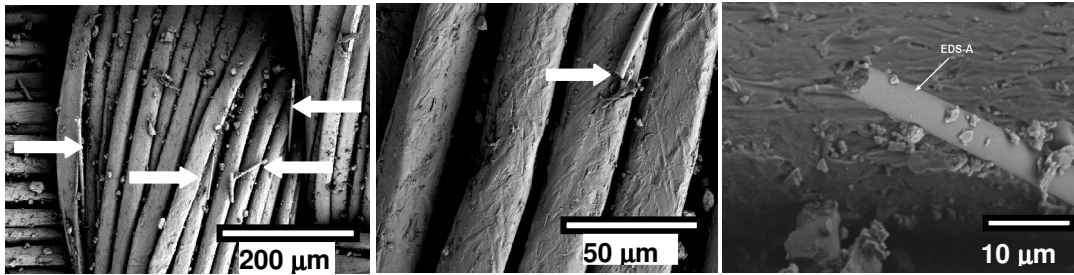


Figure 8. Secondary electron SEM images of Apollo 12 LMP ITMG outermost T-164 Teflon fabric showing fiberglass particles (arrows).

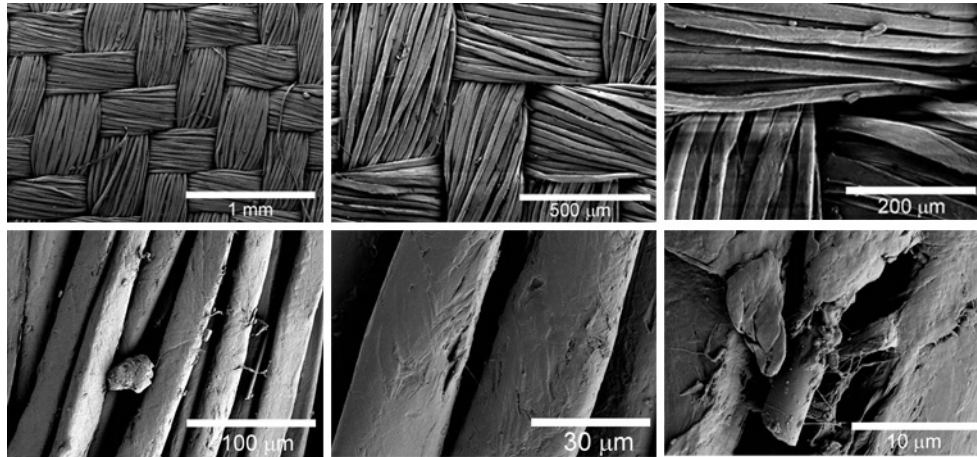


Figure 9. Secondary electron SEM images of outermost T-164 Teflon fabric from unexposed area on left shoulder on Apollo 12 ITMG that was covered by a flag patch.

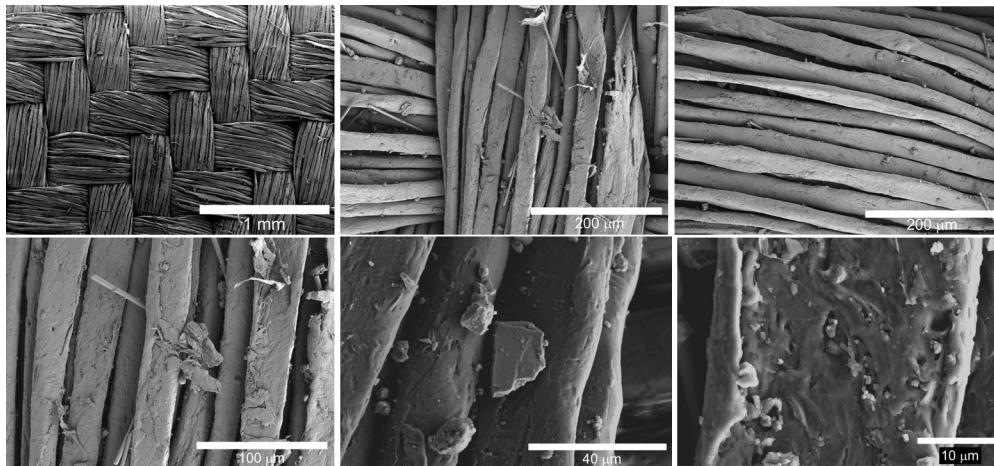


Figure 10. Secondary electron SEM images of outermost Apollo 12 ITMG T-164 Teflon fabric from exposed area on left shoulder adjacent to area covered by a flag patch.

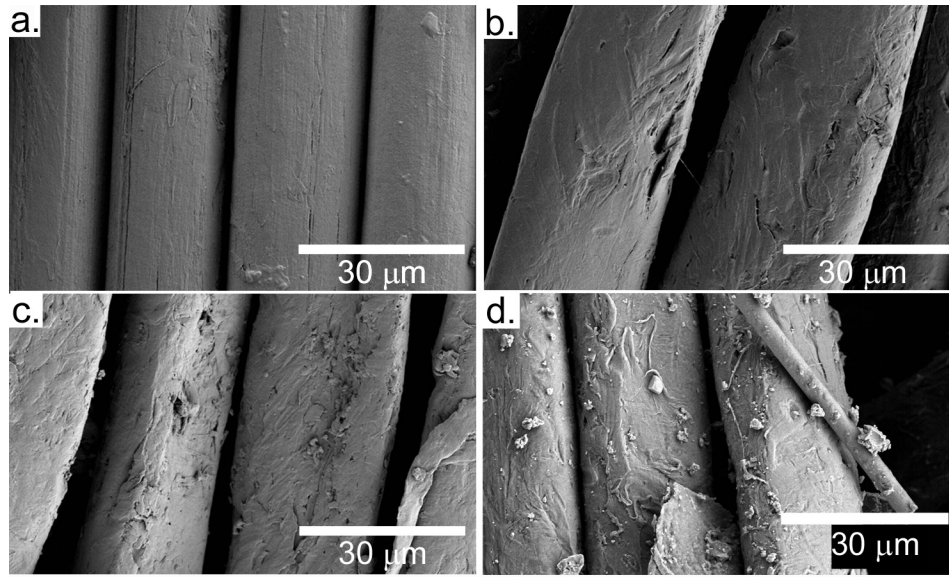


Figure 11. Secondary electron SEM images showing progressive fabric wear and damage of T-164 Teflon fabric from Apollo 12 ITMG. (a) Unused Apollo-era T-164 Teflon fabric. (b) Unexposed T-164 Teflon fabric from under flag patch. (c) Exposed shoulder area next to flag patch. (d) Left knee area with particulates and glass fiber.

entryway) was able to cause the effects observed. Grains of a lunar soil simulant (JSC1AF; Hill et al., 2007) were heavily sprinkled onto pristine, non-flight, swatches of Apollo-era beta cloth and ground into the fabric with a mortar and pestle. The fabric was then cleaned with water and a surfactant and allowed to dry. SEM examination showed features very similar to those observed on the left knee fabric (Fig. 12). Thus, while wear due to hard surface interactions remains an alternative source of the fabric abrasion effects observed, it appears that lunar soil is a possible and quite likely cause.

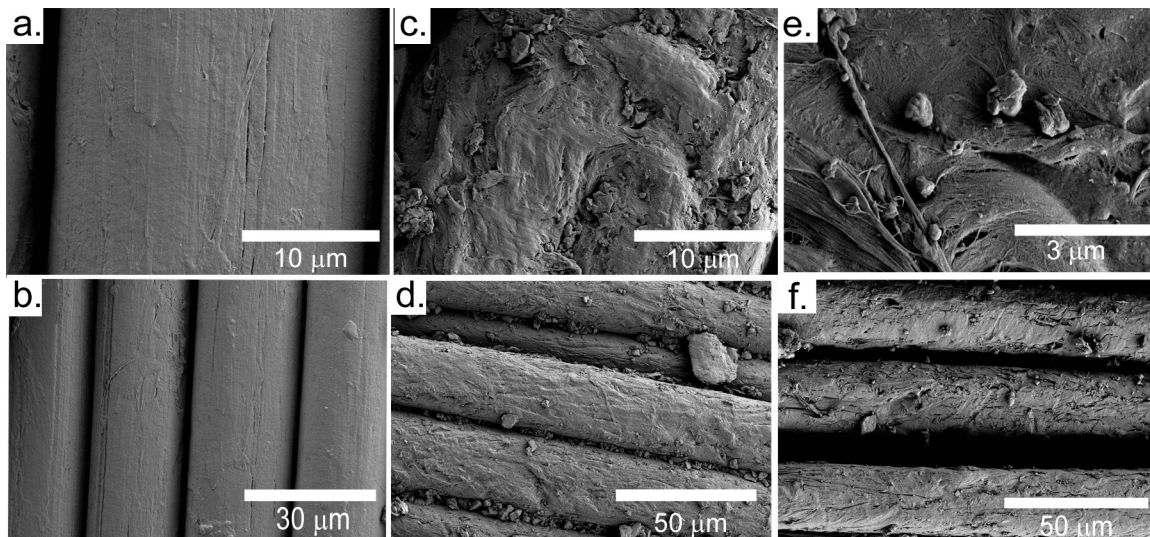


Figure 12. Secondary electron SEM images of beta cloth artificial wear test. (a) High and (b) low magnification images of pristine, unworn beta cloth. (c) High and low (d) magnification images of beta cloth artificially abraded with lunar simulant. (e) High and low (f) images of betacloth on knee area of Apollo 12 spacesuit.

Apollo 17 LMP Jack Schmitt

Visual Inspection and Optical Microscopy

Initial visual inspection and photodocumentation of the Apollo 17 LMP ITMG revealed the outer ITMG fabric to have a variably “dirty” appearance as indicated by different levels of gray discoloration of the fabric. Figure 13 shows various views of the Apollo 17 suit, including one image of a highly discolored/soiled area on the lower leg. In general, the most discolored areas of the ITMG fabric are on the

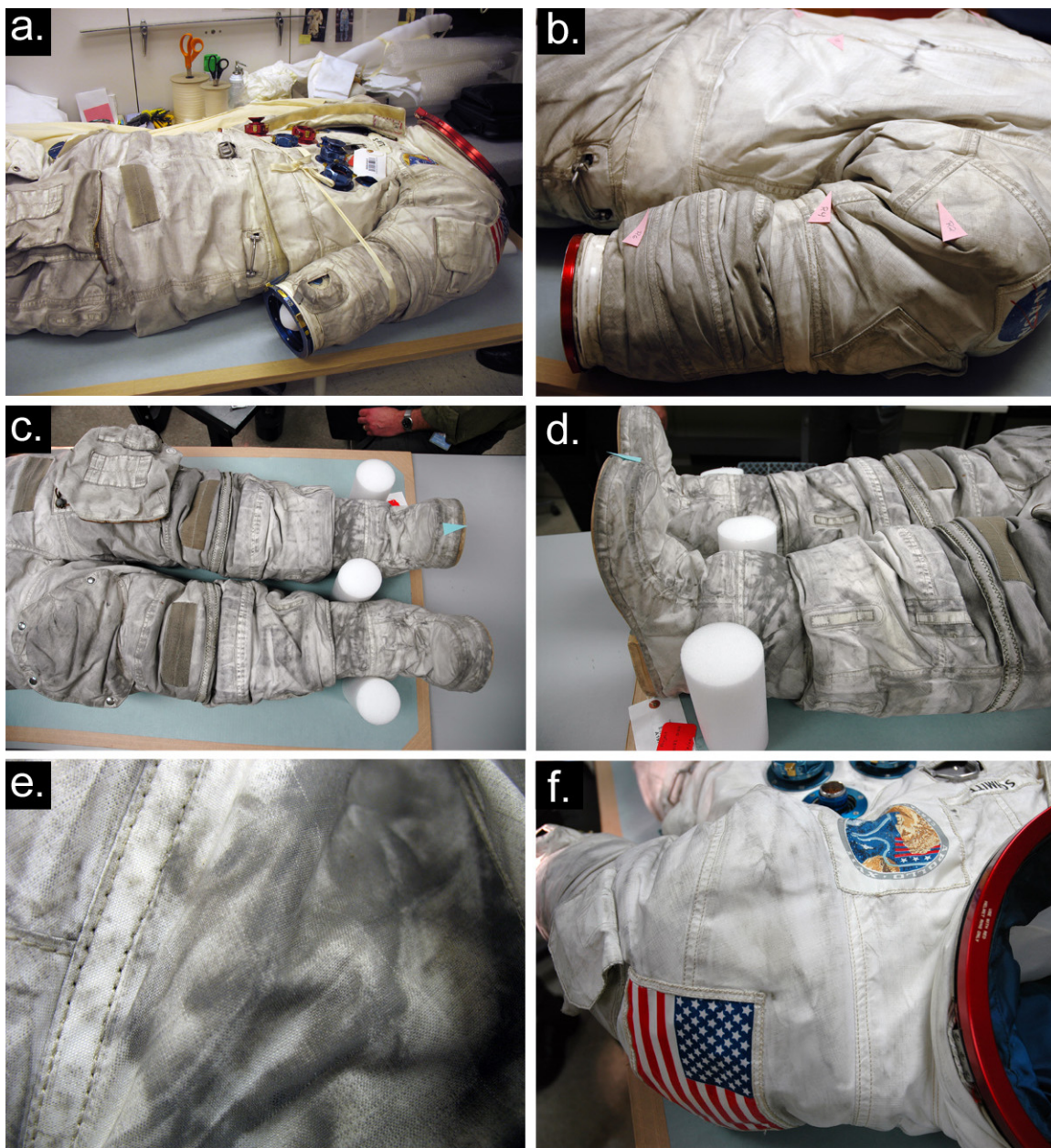


Figure 13. Views of Apollo 17 LMP A7LB spacesuit. a) Upper torso, b) upper back, c) front of legs, d) integrated pressure boots, e) close up of heavily soiled area on pressure boot, seam is approximately 1 cm wide, f) left shoulder

bottom half of the suit, but the discoloration can be very “patchy”, with local areas that are significantly less discolored than others. After preliminary visual inspection, a set of fixed locations for representative analysis of the outer fabric of the ITMG were established to coordinate and guide serial analyses by various techniques (Fig. 14). The goal was to perform analysis by several different techniques on the



Figure 14. Particle sampling locations on the outer fabric of the Apollo 17 LMP ITMG.

same area of fabric. Analytical techniques included light-optical stereomicroscopy to image the fabric, ED-XRF spectroscopy to measure variation in the integrated chemical composition of the outer fabric layers, and SEM imaging of adhesive tape-extracted samples of surface particulates. In addition, at a subset of the sampling locations, a visual gray-scale reference strip was used to roughly quantify the level of discoloration of the fabric.

Figure 15 shows a subset of the optical stereomicroscope images obtained from the fabric analysis locations in Figure 14. The images were selected using results of follow-up ED-XRF spectroscopic analyses with the applied criterion of selecting images with an even “spread” between the amounts of Ti measured at the associated fabric locations. The Ti contents in units of parts-per-million (ppm) $\times 10^2$ are listed on each image. As discussed in detail below, Ti is a likely “marker” element for lunar soil contamination because its content in the fabric scales directly with the latent amount of lunar soil. The images show that the ITMG outer fabric has a plain weave, and it was found to consist of T-164 Teflon fabric on the shoulder and knee areas of the spacesuit and 4484 beta cloth on the remaining areas. Different levels of abrasion of the fibers as evidenced by fraying are visible together with varying levels of darkening. In some cases, black particles that are likely lunar soil grains can be resolved. These and other aspects of the optical microscopy results are further discussed with the ED-XRF spectroscopy findings below.

Adhesive Tape Particle Sampling

Using the tape extraction technique described above, particle samples were obtained from the locations on the Apollo 17 ITMG outer fabric shown in Figure 14. The adhesive tape strips were prepared for SEM examination by affixing their non-adhesive sides to conductive carbon tape, and applying a thin coat of evaporated carbon to the top adhesive side containing the particles. SEM examination of the adhesive surfaces was performed using both secondary electron imaging (SEI), and backscattered electron imaging (BSE), as well as EDS analyses. The concentration of extracted particles on the tape surface was generally inhomogeneous on the 100-500 μm scale. In some cases the extracted particles formed a pattern

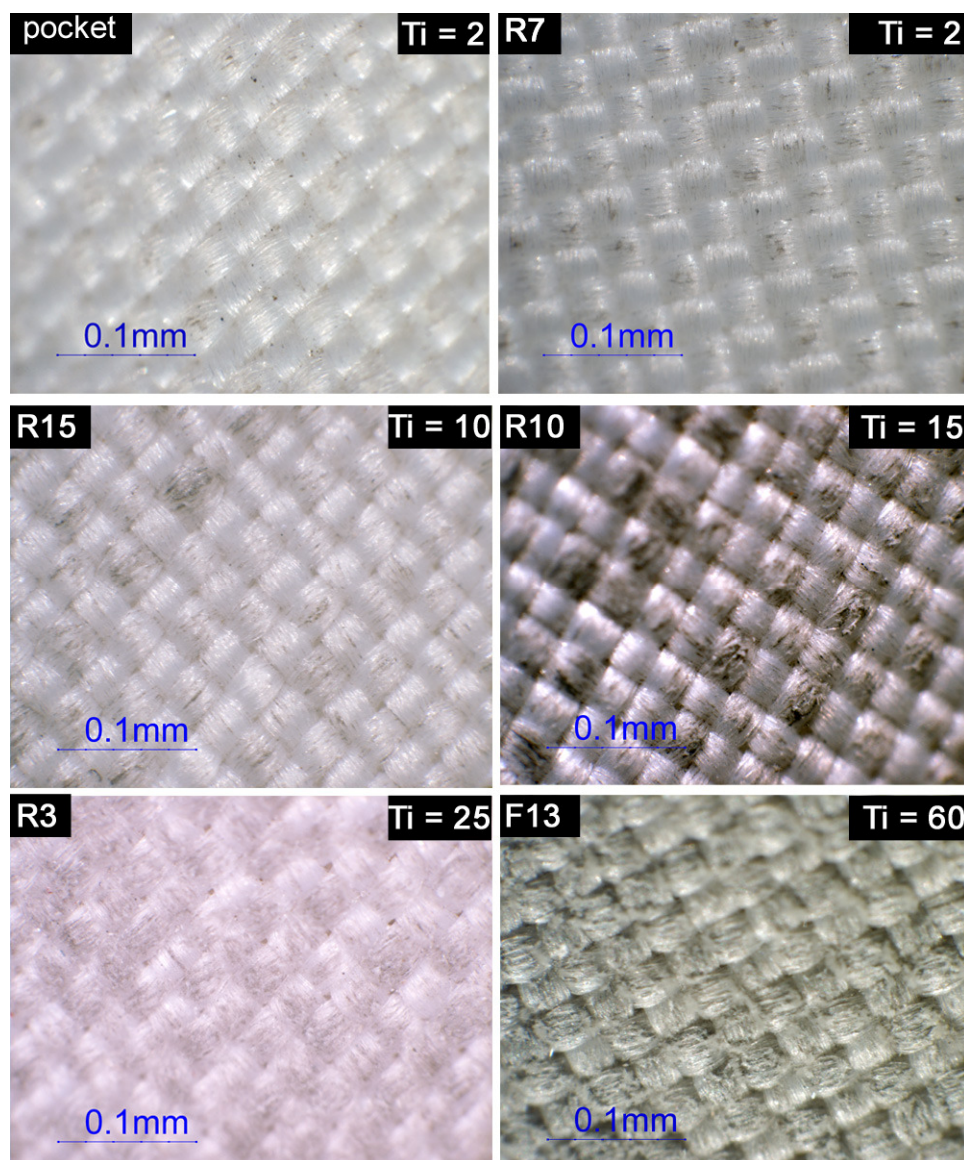


Figure 15. Stereomicroscope images of analyzed areas of T-164 teflon fabric on Apollo 17 ITMG. Number-letter designations correspond to spacesuit locations shown in Fig. 14.. The relative Ti concentration measured at each image location are in units of $\text{ppm} \times 10^2$. Image labeled “pocket” is minimally-contaminated area inside spacesuit’s front pocket. Location F13 had the highest relative Ti concentration of all analysis locations.

that reflected an imprint of the weave of the suit fabric (Fig. 16), in other instances the distribution was random (Fig. 17a).

On each strip of tape, a number of areas were selected for detailed SEM imaging. Figure 17 shows examples of areas with typical grain concentrations at different magnifications. Within a given field of view, grains were identified and categorized based on grain morphology combined with data from EDS chemical analyses. This approach was effective in identifying grains larger than $1\text{-}2\text{ }\mu\text{m}$ in size, but for smaller grains, the reduction in the X-ray excitation volume yielded insufficient X-ray counts to get reliable EDS data. For this reason, the particle type data reported here are only for grains larger than $1\text{-}2\text{ }\mu\text{m}$, with smaller particles remaining unidentified and uncounted.

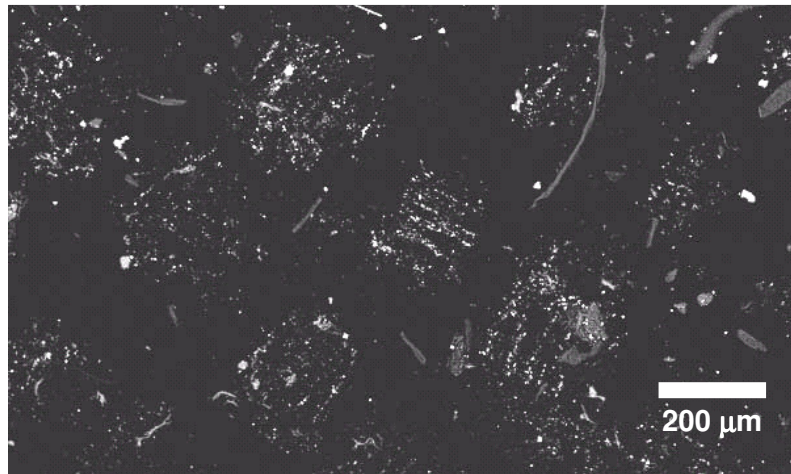


Figure 16. Low-magnification SEM backscattered electron image of surface of adhesive tape used to sample particles from the outer T-164 Teflon fabric of the Apollo 17 LMP ITMG. Particle distribution shows imprint of spacesuit fabric weave.

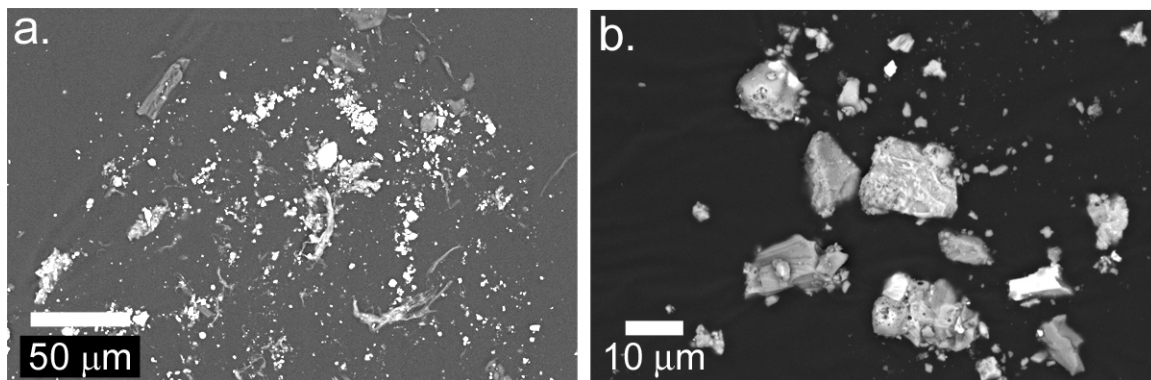


Figure 17. SEM back-scatter electron images of adhesive tape surfaces with typical particles concentrations at low (a) and high (b) magnifications.

At the highest level of classification, particles were identified as likely of lunar or non-lunar origin, with the lunar particles being further categorized and counted according to the following mineralogical types: plagioclase feldspar, pyroxene, olivine, ilmenite, or glass. SEM image examples of several of these grain types are shown in Figure 18.

An additional category of “other” was used for grains that were likely of lunar origin, but which were very minor mineral components, such as spinel and cristobalite, or complex aggregates not clearly identifiable as one of the other types. The lunar glass particles are of various morphologies and genetic types that include impact glass spherules (Fig. 18f) and fragments of impact-generated soil agglutinates (see McKay et al., 1991) (Fig. 18d, e). A total of 1,211 grains of lunar and non-lunar type were identified and categorized from the sample locations shown in Figure 14. This total population was subdivided into three groups according to the following sample locations (Fig. 14): arms (F and R sites 1-6), lower torso (F and R sites 9-12), and legs (F and R sites 13-18). The relative number counts of particle types for these three groups are shown in Figure 19.

These data include counts for non-lunar, so-called contaminant, grains that make up approximately 29% of the total grains examined. The contaminants come from several sources. Fragments of Teflon abraded from the outer fabric, likely during the lunar mission, are relatively abundant, as are short lengths of glass fibers derived from the fiberglass used in the beta cloth components of the spacesuit fabric layers

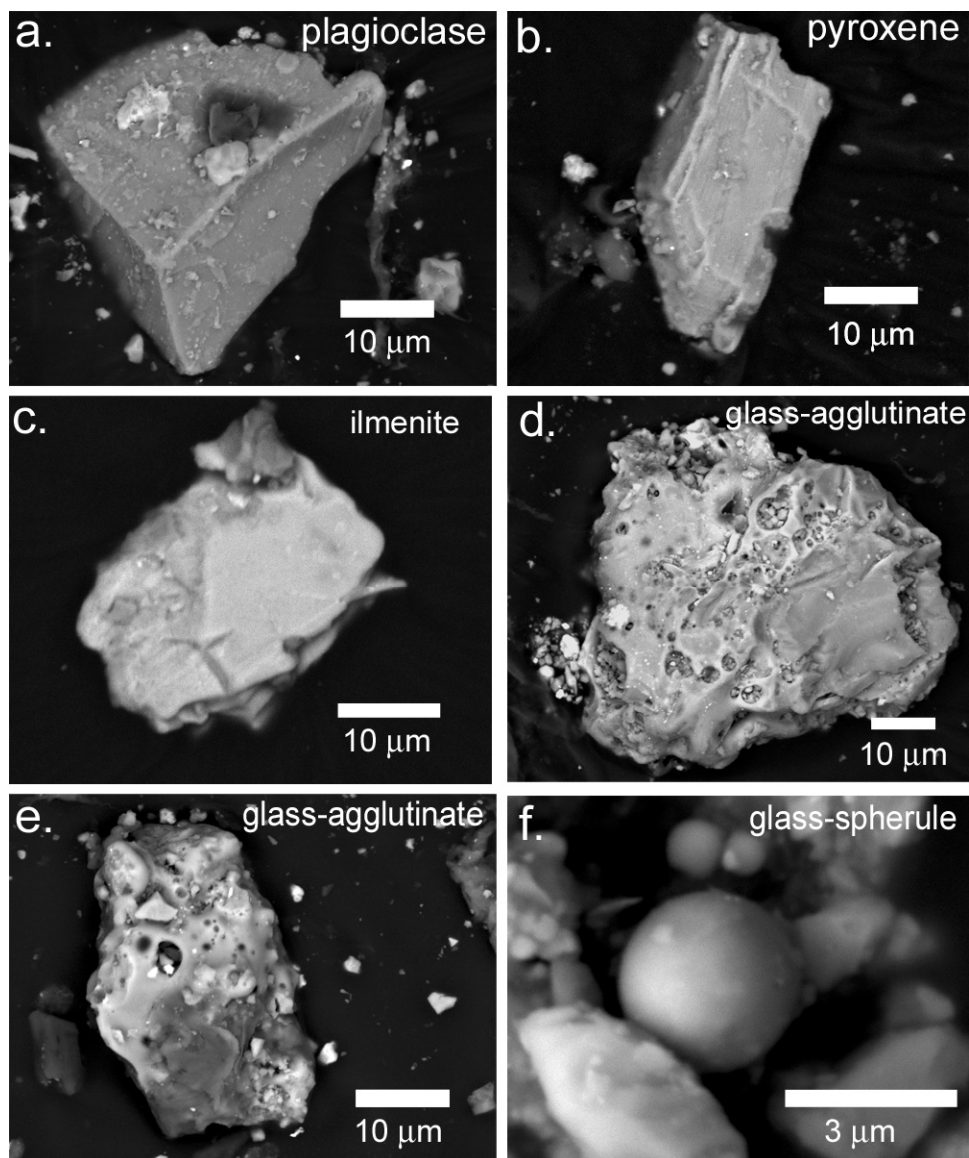


Figure 18. SEM backscattered electron images of particles of various mineralogical types from the surface of the Apollo 17 LMP ITMG T-164 Teflon fabric. (a) plagioclase feldspar, b) pyroxene, c) ilmenite, d) agglutinitic glass, e) agglutinitic glass, f) impact glass spherules.

(Fig. 20). The fiberglass particles are typically 5 µm in diameter and vary in length from 100-500 µm (Fig. 20c,d). They all have a consistent EDS signature, suggesting that they are a Ca-rich silicate glass derived from the same source. Additional non-silicate particles rich in Ca were also common. Although gypsum particles derived from building materials are a common contaminant on museum specimens, the Ca-rich spacesuit particles did not contain S in their EDS analyses, and hence are more likely to be calcium carbonate. Particles rich in sulfur, chlorine, and other elements not common to lunar soils (McKay et al., 1991) were identified as well. These were assumed to be contamination. Finally, there were deposits of KCl and NaCl and other salts derived from human sweat and other contamination sources (Fig. 20). The salts usually occur as distinctive small crystalline masses (Fig. 20d).

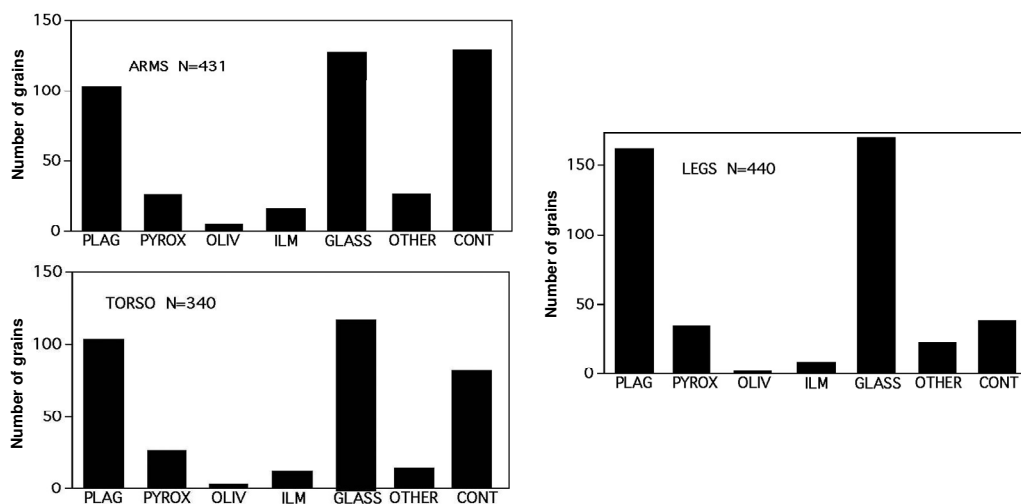


Figure 19. Relative counts for particles of different types sampled from three areas of the Apollo 17 LMP ITMG surface fabric.

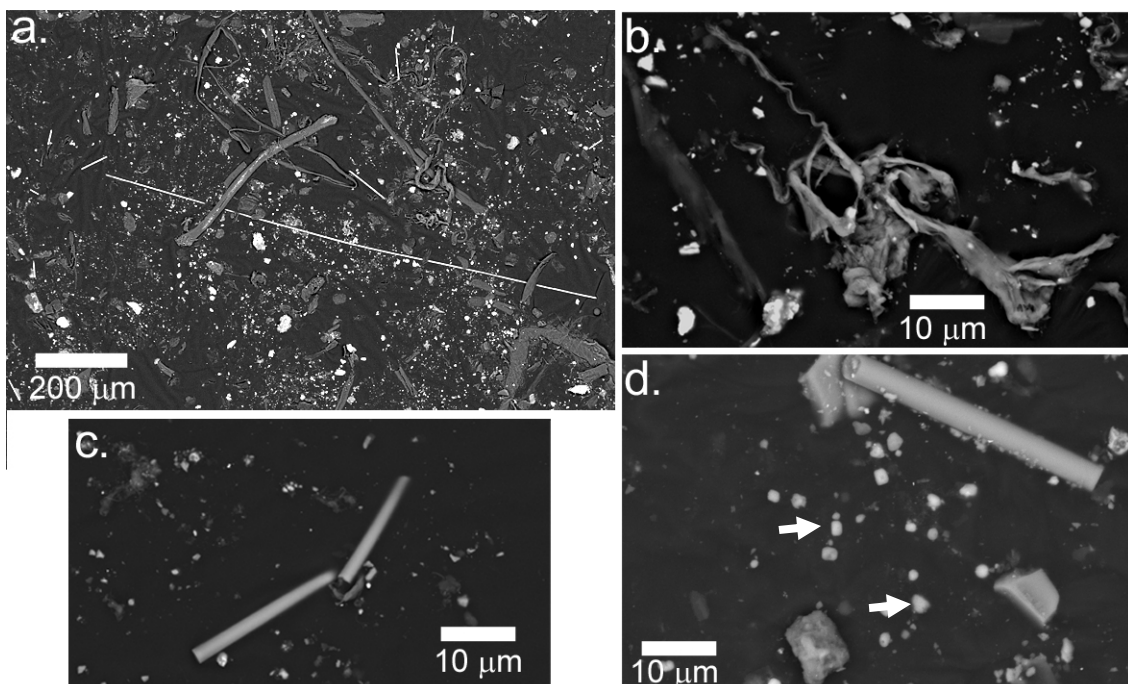


Figure 20. SEM images of non-lunar particles from Apollo 17 ITMG surface fabric. a) Low-magnification image of area containing mats of T-164 Teflon fibers and fiberglass fragments along with lunar grains, b) Teflon fibers, c) fiberglass particle, d) KCl particles (arrows) adjacent to fiberglass particle.

There appeared to be little variation in the relative grain-count frequency distribution of grain types sampled from the different areas of the suit. Across all areas, the largest numbers of particles by far are plagioclase feldspar and lunar glass of all types. Taken together, these two groups form close to 80% of the total number count of lunar particles at all locations (Fig. 19). The third major particle type is pyroxene. Minor minerals include olivine and ilmenite, with trace amounts of cristobalite and spinel, the latter two minerals being grouped in the “other” category.

The grain size of the lunar particles on the tape surfaces was determined using high contrast backscattered electron images that were processed using the particle measuring routine in *ImageJ* software. The

population of 846 confirmed lunar grains has a mean grain size, based on diameter, of 10.7 μm with a median of 8.3 μm and a mode of 5.5 μm (Fig. 21). Qualitative review of the *ImageJ* data acquired from different areas of the suit suggested the size distributions are relatively uniform across all sampled areas.

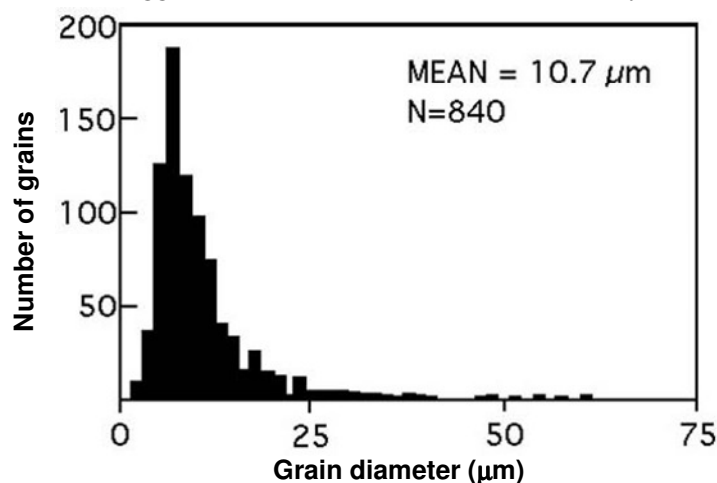


Figure 21. Size distribution of lunar grains obtained from outer surface of Apollo 17 ITMG by tape sampling.

As noted above, because EDS analysis limitations do not permit determining whether smaller (1-2 μm) grains are lunar or non-lunar, data for these smaller grains are not included in Figure 21, or in computation of the mean. The true mean particle diameter is therefore likely to be considerably smaller than 10.7 μm .

Although separate grain size analyses were not performed for different particle types, it was noted that pyroxene grains, although lower in particle count than plagioclase and glass, were significantly larger in size than other grain types. Therefore, on a relative grain volume or modal basis, they were the dominant type of mineral on the suit fabric. This finding is reflected in the modal (volume %) mineralogy data obtained by processing the *ImageJ* data to obtain relative volumes from the mean diameters by assuming spherical particles (Fig. 22). A comparison of these data to the modal mineralogy of two representative Apollo 17 soils in the 10-20 μm size range (Taylor et al., 2001) shows that the ITMG fabric is indeed strongly enriched in pyroxene relative to soil at the Apollo 17 EVA site (Fig. 22). In addition to this key difference, there is also a much smaller modal abundance of lunar glass of all types on the fabric relative

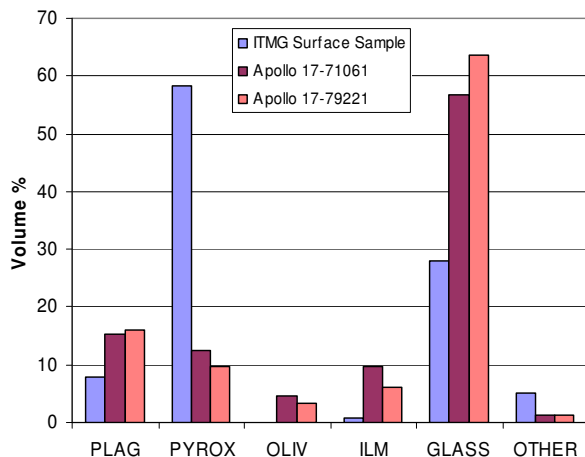


Figure 22. Modal (volume %) mineralogy of tape-extracted particle samples from Apollo 17 LMP spacesuit ITMG outer fabric compared to representative Apollo 17 soil samples from Taylor et al. (2001).

to what is found in the lunar soil. Overall, the data indicate that the ITMG fabric lacks glass particles of comparable size to the pyroxene grains found on the fabric. This is a notable difference from the lunar soil, in which large glassy agglutinates that match the size of soil mineral grains are relatively common (McKay et al., 1991). It would therefore appear that the fabric is less able to retain these larger glass particles relative to pyroxene grains of the same size. A possible explanation for this is that on a size-to-size comparison, the glass particles are more friable than the stronger crystalline pyroxene grains, and are therefore more likely to comminute into smaller grains that leave the fabric when it is brushed or rubbed.

X-ray Fluorescence Chemical Analysis

As part of the ED-XRF spectroscopy analytical strategy for the Apollo 17 ITMG fabric, a set of preliminary tests were performed to determine which analyzable lunar soil elements were the best markers to use as measures of the level of soil contamination on the fabric. The prime candidates were Ca, Ti and Fe, which all have major element concentrations in lunar soil (McKay et al., 1991; Taylor et al., 2001). In determining whether these elements were suitable, and whether the overall strategy would work, the absolute level and variability of the background concentration of these elements in the spacesuit materials were analyzed. To determine this, ED-XRF spectroscopy analyses were performed on two types of “blank” materials: various combinations of “reference fabric stacks”, comprised of different combinations of unflown ITMG fabric, and an area from inside a pocket on the ITMG of the actual spacesuit that was considered to be the least contaminated area on the suit. In Figure 23 a plot of the energy-dispersive X-ray fluorescence spectrum for Ca, Ti, and Fe obtained on a reference stack containing all of the ITMG fabrics layers is compared to a plot for the “clean” area on the actual spacesuit. Included for comparison

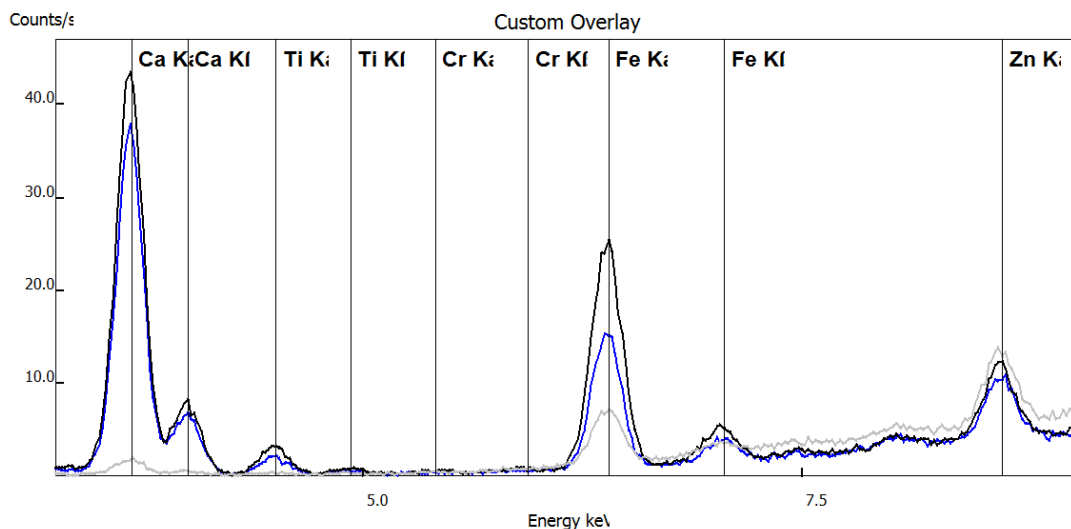


Figure 23. ED-XRF spectra of Apollo 17 LMP ITMG outer fabric showing spectra obtained from clean pocket area (blue trace), dirty area outside pocket (black trace), and spectrum of spacesuit fabric reference stack (gray trace). Vertical lines show markers for ED-XRF secondary X-ray peaks for various elements.

is a spectrum for a “dirty” fabric area adjacent to the pocket. The reference stack spectrum shows the presence of appreciable Ca, a lesser amount of Fe, and no detectable Ti. In contrast, the clean reference spot inside the spacesuit contains a small amount of Ti in addition to Ca and Fe. The latter result may indicate that compositionally-measurable lunar soil is present on or below the pocket fabric even though it appears visibly clean. Alternatively, the fabric layup under the pocket may contain some Ti-bearing components or contaminants that are not present in the unflown stack of ITMG fabric.

Overall, the preliminary tests suggested that Ti was likely to be the best marker for lunar soil contamination, based on its low background in the uncontaminated suit material. Iron was also considered to be a potential marker, but Ca was ruled out on the basis of its significant concentration in the fabric refer-

ence stack. These preliminary conclusions were further confirmed based on trends in the ED-XRF dataset obtained for the entire spacesuit (see below).

The ED-XRF spectrometer was used to obtain compositional measurements on the tape-sampled locations shown in Figure 14, as well as on some additional areas. Although measurements were made both in the so-called soil and LEAP modes, the LEAP data are reported here due to lower penetration depth through the fabric and superior sensitivity to elements of interest. All measurements were performed prior to tape sampling.

The ED-XRF software converts X-ray peak intensities to element concentrations in parts-per-million (ppm) based on the spectrometer's calibration routine. As previously discussed, there are several sources of uncertainty in the methods by which the raw ED-XRF data are quantified, and for this reason, the measured element concentrations should be viewed mainly as relative values useful to evaluate comparative trends. The ED-XRF analyses uncovered a significant range of variation in the concentration of Ca (2500-17,000 ppm), Ti (240-6,300 ppm) and Fe (850-10,000 ppm), strongly suggesting that these three elements are significantly linked to the amount of lunar soil contamination on the spacesuit fabric. However, as noted above, of the three elements, Ti has the lowest background in the un-contaminated fabric



Figure 24. Concentration of Ti in units of $\text{ppm} \times 10^2$ measured by ED-XRF for tape-sampled location on front (left) and back (right) of Apollo 17 LMP ITMG (see Fig. 14).

and is therefore likely to be the more sensitive chemical marker to use as a proportionate measure of the amount of latent lunar soil in the fabric. This hypothesis was further confirmed based on chemical variation plots for the entire set of analyses which showed that when the relative ratios of Ca/Ti and Fe/Ti were each plotted against absolute Ti, both ratios reach relatively constant “plateau” levels at very low values of absolute Ti. The plateau value in this case likely represents the intrinsic element ratios of the lunar soil contaminant, and the relationships in the plots are consistent with a very low intrinsic background for Ti.

Using Ti as a compositional marker for lunar soil contamination, Figure 24 shows maps of the Ti concentrations corresponding to the tape-sample locations on the front and back of the Apollo 17 ITMG. The concentration values are given in $\text{ppm} \times 10^2$ based on one significant figure precision. There is overall excellent correlation between the Ti concentration numbers and areas of the suit that appear substantially more “dirty” based on visual inspection. These areas include the lower legs and lower back, both portions of the suit where a high amount of contact with soil would be expected. The correlation is additionally confirmed if the fabric gray scale color values for several of the sampled locations are plotted against measured Ti concentration (Fig. 25). Although there is some spread in the Ti concentration values at each gray level, a general positive trend is apparent. The overall results confirm ED-XRF as a poten-

tially useful tool for measuring lunar soil contamination on other spacesuits, and in other applications involving fabrics, or laminated materials such as carbon composites.

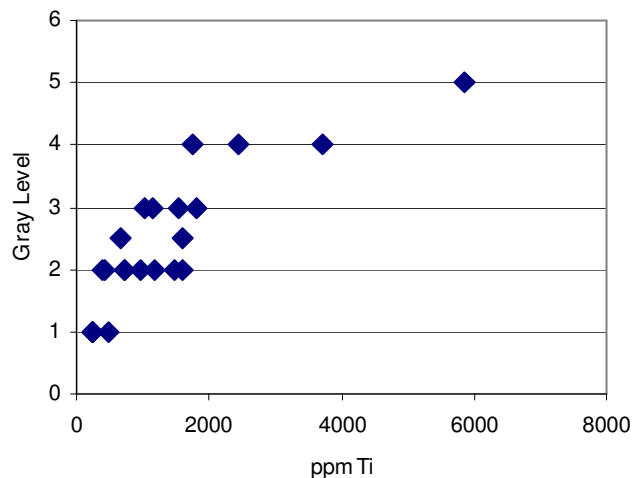


Figure 25. Visually-estimated gray level of Apollo 17 spacesuit outer fabric ED-XRF analysis locations plotted against measured Ti content in parts-per-million (ppm).

Pressure Glove Results

Background

The Apollo spacesuit pressure gloves were of interest in the current study because, like the lunar boots, they represent a component of the Apollo spacesuit that had significant direct interaction with the lunar surface. Also, unlike the ITMG, which was worn during certain phases of IV as well as EV operations, the EV pressure gloves were worn only on the lunar surface, and so experienced wear and abrasion effects that were more exclusively the results of lunar surface operations, without complicating effects from use inside either the LM or CM. The presence of a sealed mechanical rotation bearing in the glove assembly was of particular interest as a test case to determine whether lunar soil particles could enter past the bearing seals and cause increased wear and abrasion of the bearing working parts.

The Apollo lunar EVA crews were provided with one set of intravehicular (IV) pressure gloves and one set of extravehicular (EV) pressure gloves (Fig. 26). The IV pressure gloves were worn with the spacesuit PGA in the CM when operations such as launch or docking required protection against the risk of cabin de-pressurization. They were also worn in the LM during lunar descent and ascent. The IV pressure gloves consists of neoprene rubber pressure bladder material that was molded to the wearer's hand and permanently integrated with a metal cuff assembly containing the male end of a quick-disconnect coupling for mating to the spacesuit PGA (Fig. 26). Convolutes in the bladder material in the wrist area provide omni-directional flexure for wrist movement. In addition, the male end of the quick-disconnect has an integrated sealed bearing termed the "inner race" that permits 360° glove rotation (Fig. 27). It was this bearing that was disassembled and characterized as part of the current study.

The EV glove assembly was donned exclusively for lunar EVA operations and consisted of a second, modified IV glove integrated with a multi-layered fabric shell that had three different types of material comprising its outer materials assembly (Fig. 26): 1) thumb tip and fingertip hard coverings made of silicon-rubber-coated nylon tricot, 2) coverings on palm, thumb and back of the hand made of woven chromel-R metal fabric (coated with silicone rubber on the palm and thumb to improve grip), 3) a fabric gauntlet made of beta cloth that extended far enough up the arm to completely cover the inner race and the male-female quick-disconnect hardware that mated the glove to the rest of the suit. Optical microscope and SEM examination of selected areas of the outer materials on two EV gloves was performed in

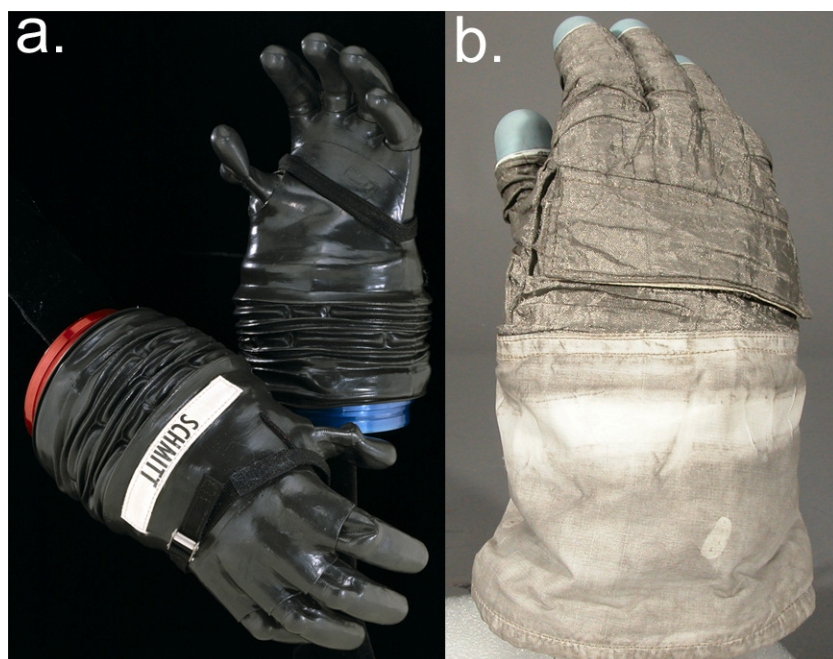


Figure 26. Examples of the two types of Apollo spacesuit pressure gloves. a) Apollo 17 LMP intravehicular (IV) pressure gloves, b) Apollo 17 LMP extravehicular (EV) pressure glove. (Official Smithsonian images used by permission).

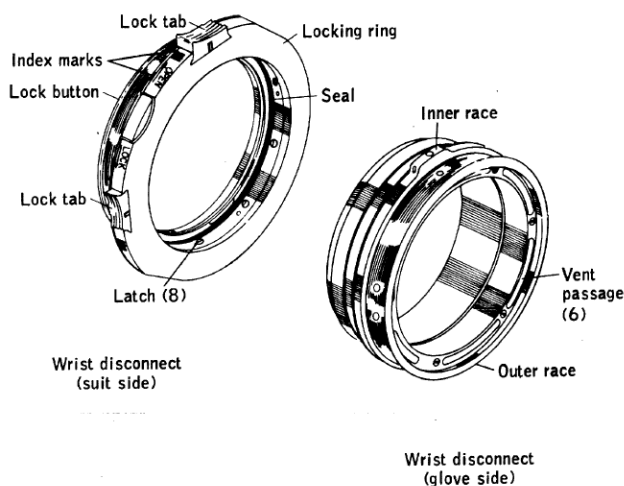


Figure 27. Apollo spacesuit pressure glove wrist disconnect assemblies

order to assess wear performance of these materials as possibly influenced by interaction with the lunar surface and lunar soil in particular.

EV Glove Outer Materials

The outer fabric materials on the right-hand and left-hand EV pressure gloves worn by the Apollo 17 LMP were studied by microscopic imaging. SEM imaging techniques were used for the right-hand glove and light-optical stereomicroscope techniques were used for the left-hand glove. SEM study of the right-hand glove was performed using an Hitachi Model S-3700 SEM at the Smithsonian Institution Museum Conservation Institute. The sample chamber on this instrument was large enough to accept the entire glove without any disassembly, but restrictions on the glove position limited imaging mainly to areas of

Chromel R fabric covering the back of the hand, with some access to adjacent areas of Velcro® (Velcro Industries B.V.) and beta cloth. The portions of Chromel R fabric imaged by SEM were those that lacked the silicone-rubber grip coating used on other areas of the glove, thus affording the opportunity to study the Chromel R fabric in its native state.

Key features of the glove Chromel R fabric areas imaged by SEM are shown in Figure 28. Among the observations were broken Chromel R metal threads that had been pulled out of the weave (Fig. 28a). The absence of separate thread fragments in areas associated with these broken fibers suggests either that the breakage occurred during manufacturing, or that the loose fibers, once pulled out of the weave, are easily broken by fatigue. Other features more likely to have been produced during the missions are sets of scratches and scoring perpendicular to the threads, especially on the “high points” of the weave (Fig. 28b). The consistent parallel alignment of the scratches and the relative hardness of the Chromel R metal fibers makes it more likely that these features resulted from handling or actuating high-hardness metal

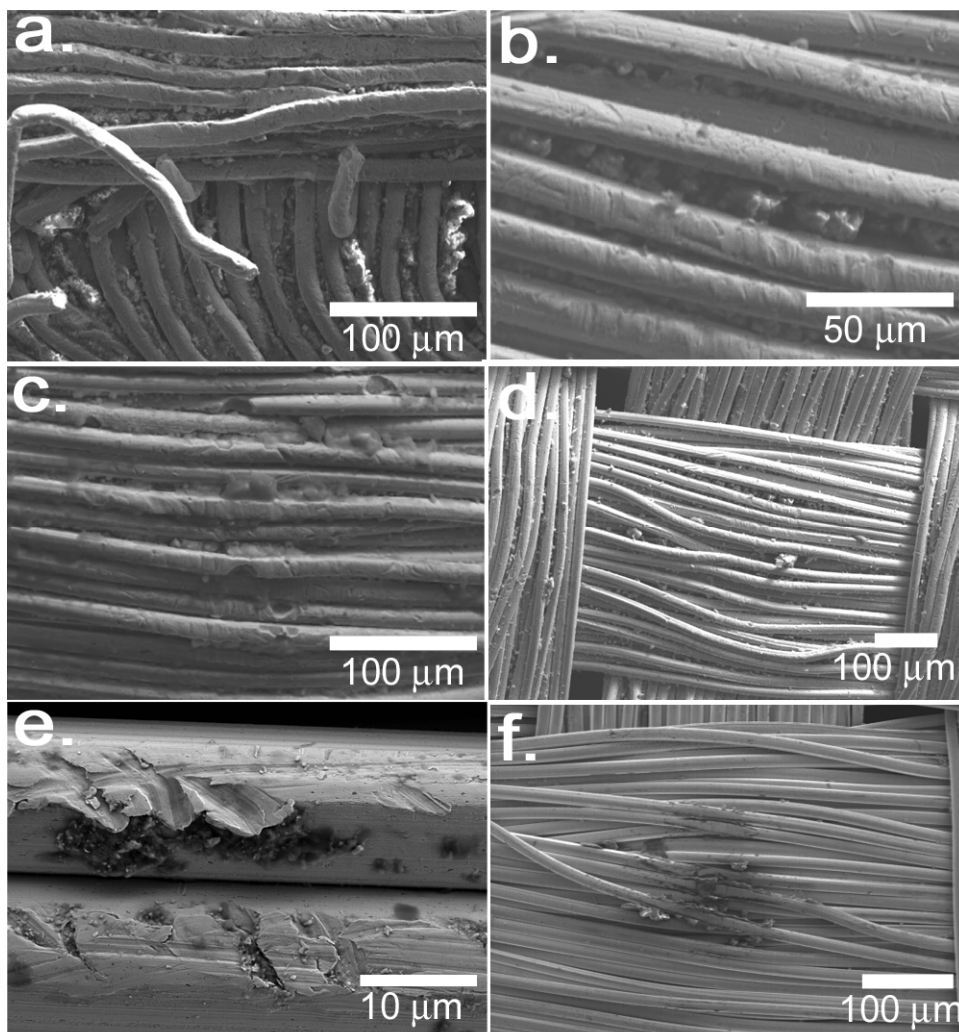


Figure 28. SEM secondary electron images of Chromel R fabric used in Apollo EV pressure glove. Images (a,b,c,d) show Chromel R fibers on backside of Apollo 17 LMP EV pressure glove. Images (e,f) show Chromel R fibers on stock piece of Chromel R fabric subjected to typical wear and contamination from normal handling in the JSC Crew and Thermal Systems division.

surfaces on tools or instruments, rather than having been the result of interaction with lunar rocks or soil. In addition to multiple, fine-scale scratches, isolated semi-circular “pits” were found on some fibers (Fig. 28c). Although initially considered to be a possible result of chemical corrosion, such an origin would most likely be associated with formation of oxidation layers or reaction zones, which are not observed. More likely, these features are a result of mechanical wear associated with impact, pulling or cutting against a sharp tool or instrument.

Particulate material trapped just inside or between individual Chromel R threads was typically observed in all of the areas of the glove imaged by SEM (Fig. 28b,c,d). These particles ranged up to 20 μm in diameter, with dominantly equi-dimensional, angular shapes. However, “smooth” material that appeared to form fillings or coating between the fibers was also observed (Fig. 28c). Because the EDS spectrometer on the Smithsonian SEM was only newly installed and not fully functional, it was not possible to chemically analyze the observed particles to determine whether they were lunar soil grains or terrestrially-derived contamination. However, many grains had shapes identical to lunar grains studied on the ITMG suit fabric, so it is likely that a significant proportion of these grains are of lunar origin.

Based on SEM imaging, the Chromel R fabric portions of the Apollo 17 EV glove show evidence of significant physical wear and abrasion. In order to obtain a baseline reference on the wear performance of Chromel R fabric under non-flight conditions, a stock piece of the fabric that had been subject to light physical handling in the JSC Crew and Thermal Systems Division was studied by SEM imaging. The results showed that under everyday handling, the Chromel R fibers, although significantly less abraded than those on the Apollo 17 flight-article glove, nonetheless showed nicks and scratches in some areas (Fig. 28e), as well as accumulations of particulates on the “high” spots of the fabric weave (Fig. 28f). The overall impression is that the Chromel R fibers are moderately susceptible to contamination and wear even under light use.

Optical stereomicroscope imaging of the left Apollo 17 EV glove provided the opportunity to characterize areas such as the palm, fingertips and gauntlet that were not accessible by SEM. The light-optical images, which have considerably lower resolution than those obtained by SEM, nevertheless revealed additional wear and contamination features such as abraded areas of the silicone-rubber coating on the glove palm (Fig. 29a), large accumulations of particulate contamination on the remaining areas of silicone-rubber coating (Fig. 29b), tears in other areas of the Chromel R fabric (Fig. 29c), and black particulates on the gauntlet fabric and Velcro that are likely lunar soil (Fig. 29d,e). Images of the nylon tricot finger tip material showed a significant number of gouges and scratches (Fig. 29f). The overall findings suggest relatively significant abrasion, wear and contamination problems with other glove components in addition to the Chromel R metallic fabric.

Glove-Side Wrist Disconnect Rotation Bearing

Mechanical assemblies that provide for detachable or moving pressure seals represent systems that may be affected or compromised by contamination from lunar dust particles. Two such assemblies are incorporated in the Apollo spacesuit glove designs. The first is a male-female lockable mating system that attaches a male connector on the glove itself to a female locking ring on the arm of the spacesuit (Fig. 27). A pressure seal is provided by an O-ring system on the female side. The second is a non-detachable, sealed rotation bearing incorporated into the glove itself, next to the male connector (Fig. 27). This rotation bearing is designed to maintain a pressure seal while at the same time providing for rotation of the astronaut’s hand and forearm relative to the elbow joint. Although in most humans this rotation is limited to about 90° clockwise and 180° counter-clockwise hand rotation, the rotation bearing nevertheless provides for continuous 360° rotation.

Of the two assemblies, only the detachable glove lock system was directly noted by Apollo crews to experience “clogging” effects from lunar dust (Gaier, 2005). This has led to some interpretations that higher-than-normal suit pressure decay experienced by some crews was due to compromise of seals by lunar dust (Gaier, 2005). In the current study, we were unable to effectively evaluate lunar dust effects in the glove-lock system because of limited access to the female part of the mechanism. We were, however, interested and able to determine whether, absent of any directly reported functional problems, the glove

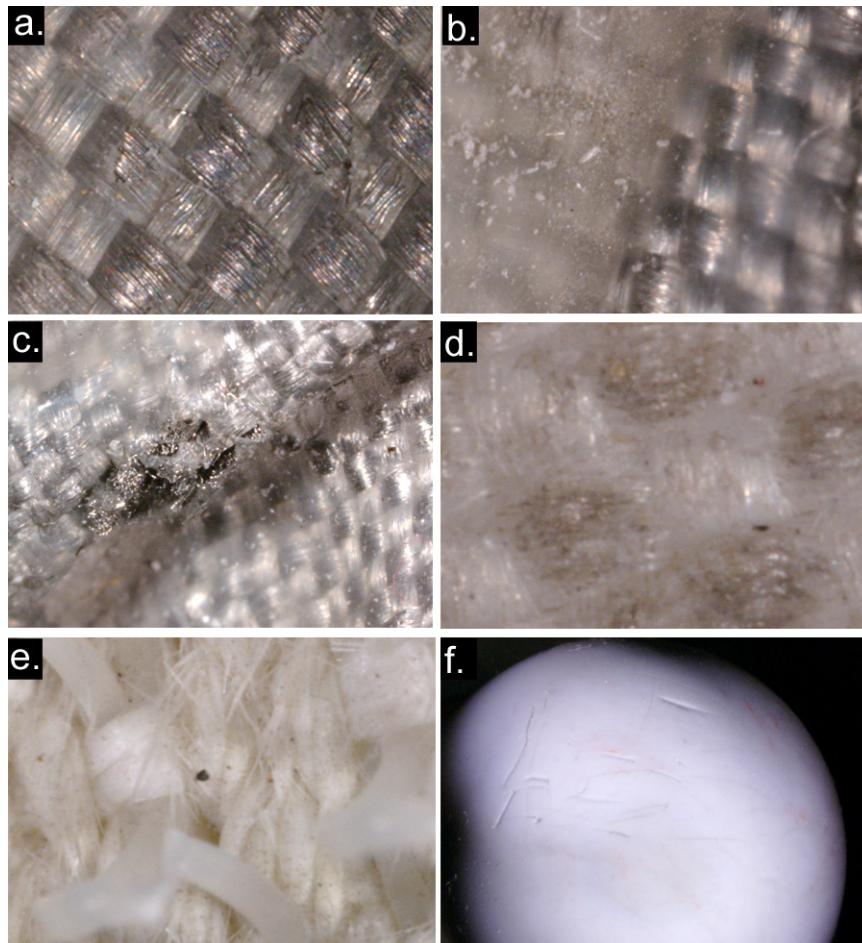


Figure 29. Optical stereomicroscope images of areas of exterior fabric on Apollo 17 LMP EV pressure glove. a) Chromel R fabric with silicone rubber coating, arrow shows areas where coating abraded away, b) silicone rubber coating on chromel R fabric with particulate contamination, c) tear in chromel R fabric, d) beta-cloth on glove gauntlet with dark particulate grain (arrow), e) velcro fabric with dark grain (arrow), f) nylon tri-cot finger tip hard shell with scratches and gouges.

rotation bearing had experienced marginally increased mechanical wear due to lunar dust contamination. This determination was conceived as a test of two integrated, combined, issues: 1) whether lunar soil particles were capable of working themselves past the elements of the rotating pressure seal to enter the “inner race” of the metal bearing itself, and 2) whether increased abrasion and wear of the bearing could occur as a result.

The rotation bearing investigation was performed using flight-article EV and IV pressure gloves worn by Apollo 16 LMP Charles “Charlie” Duke. The necessary disassembly/reassembly of the gloves was authorized by the Smithsonian on the basis that it could be done with no loss of material or permanent damage. Because it was never worn on the lunar surface, the rotation bearing inside the IV glove was used as a control to compare to the bearing of the EV glove, the latter having been worn for a total of 19.3 hours on the lunar surface (Table 3).

Disassembly of the rotation bearings was performed by an experienced NASA spacesuit technician and involved opening the ball-bearing insertion port to remove the ball bearings and Teflon spacers to allow separation of the two halves of the bearing (Fig. 30a). Once the inner bearing with its half of the

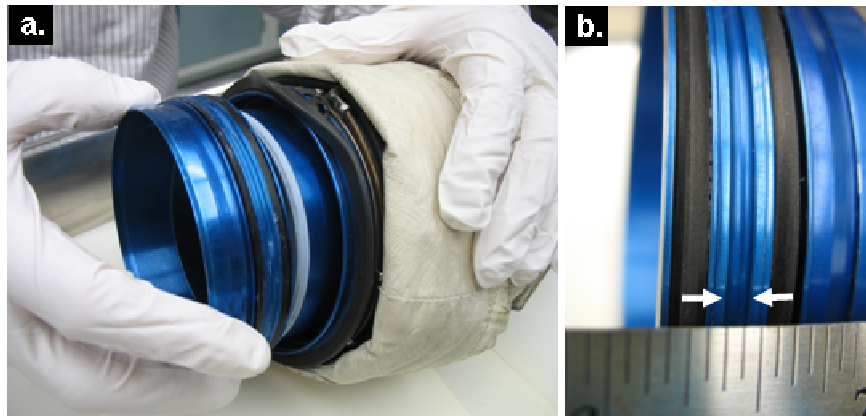


Figure 30. View of disassembly (a) and bearing surface (b) of the Apollo 16 LMP EV pressure glove wrist rotation bearing. Arrows in (b) indicate the sides of the “race” in which the ball bearings are seated. Ruler scale is calibrated in 1/16 of an inch.

ball-bearing race was separated, its coating of Krytox® (E.I. du Pont de Nemours and Company) lubricating grease was very effectively removed using Vertrel XF® (E.I. du Pont de Nemours and Company) degreasing solvent. Although records suggest that the Apollo 16 glove bearings were disassembled and cleaned after the mission (Lirado, 1972), in the current study we made an effort to initially rinse the bearing surface such that any particles in the rinsate were deposited on a Nucleopore® (Whatman Inc.) filter for later examination. Subsequent examination of the filters showed no lunar particles.

As shown in the close-up image in Figure 30b, the surface of the inner bearing consists of a semi-circular trench ~2 mm wide that comprises the inner half of the ball-bearing race. The race trench is bounded by raised shoulders, with additional adjacent trenches and ridges machined into the aluminum that support the interleaved O-ring seals. The wear surfaces of interest consist of the bottom and side walls of the race trench where the ball bearings make contact. SEM imaging was judged to be the preferred technique for examination of these surfaces, and the bearing was mounted in a special bracket that enabled the race surface to be tilted into position for imaging in the JEOL 5910LV SEM at NASA-JSC. In addition to the race surface of the inner bearing, a set of eight ball bearings each from the EV and IV glove bearings were also studied by SEM. Although the bearing is composed of an aluminum alloy that ordinarily does not require application of a conductive coating for SEM examination, the aluminum has an anodized surface that is relatively less conducting. Because application of a carbon coat to the bearing would compromise Smithsonian curation requirements, SEM imaging experienced local charging effects that limited the length of time the electron beam could be kept on a given area. The effects were, however, not severe enough to prevent high-quality images from being obtained.

SEM secondary-electron images of selected areas of the race trenches from both the IV and EV glove bearings are shown in Figure 31. The most notable features in the anodized aluminum surfaces of both the IV and EV trenches are varying densities of parallel grooves 1-10 μm in width which are aligned with the axis of the trench. After some analysis and review that included consultation with metallurgists at NASA Glenn Research Center, these grooves are interpreted to be machine tool marks associated with the original lathe machining of the bearing aluminum. In addition to the machining marks, networks of surface cracks resembling the “crazing” on ceramic glazes are visible in the images in Figure 31, b–d. Crazing of anodized coatings is a well-known artifact of the anodization process and results from differences in the thermal expansion between the anodized coating, which is an aluminum oxide, and the underlying aluminum metal. In the present case the crazing became increasingly visible as the surface became progressively charged under the electron beam.

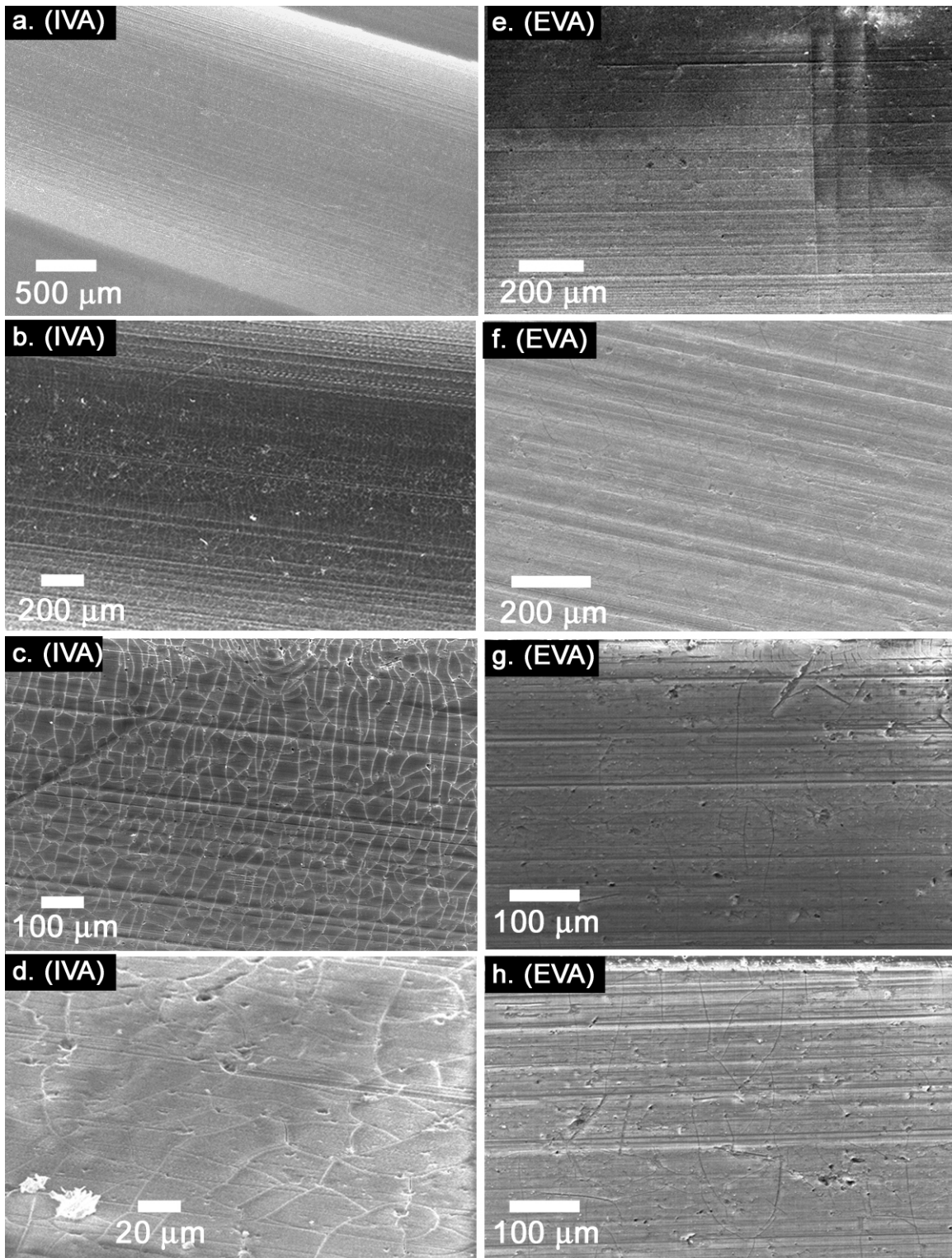


Figure 31. SEM secondary-electron images of surfaces on the bottom and sides of the ball-bearing race in the wrist-rotation bearing from the Apollo 16 LMP pressure gloves. Images a. – d. (IVA) are from the bearing race in the IV pressure glove. Images e. – h. (EVA) are from the bearing in the EV pressure glove.

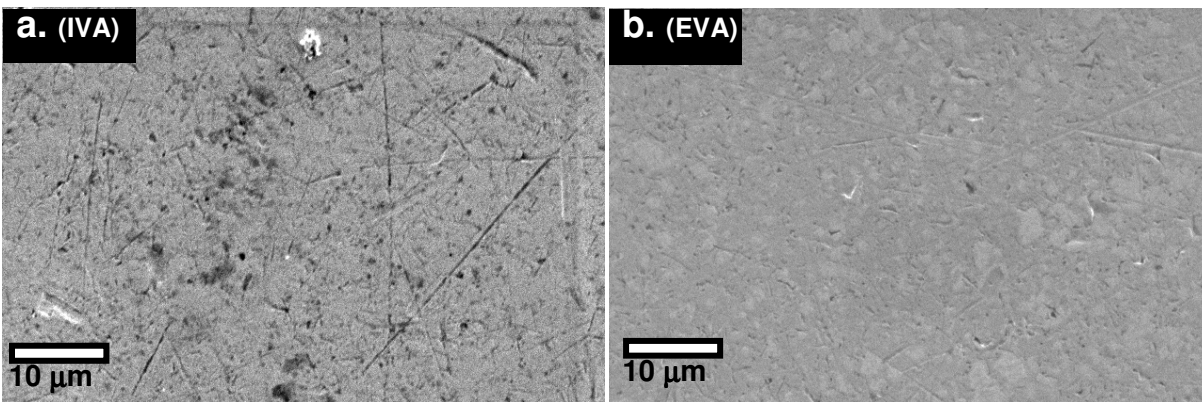


Figure 32. SEM secondary-electron images of surfaces of ball bearings from the Apollo 16 LMP IV pressure glove rotation bearing (a), and EV pressure glove rotation bearing (b).

Detailed comparisons of the SEM images from both the IV and EV bearing trenches revealed no key differences that could potentially indicate accelerated abrasion, scratching or surface wear of the EV bearing compared to the IV bearing. The number and width of the machining grooves, although somewhat greater on the walls compared to the bottom of the race, are similar on both parts. Both pieces also contain relatively equal numbers of additional random discontinuous scratches, dents and grooves oriented at various angles to the machining grooves. Surface pits of various sizes and densities are also present in both the IV and EV bearings, and in some cases, these pits form the starting points for slightly deeper and wider machining grooves, possibly because impact with the pit caused the edge of the machine tool to cut slightly deeper.

Secondary electron images of the surfaces of ball bearings from the IV and EV bearings are shown in Figure 32. Ball bearings from both gloves exhibit varying densities of randomly oriented scratches. In Figure 32, the density of scratches is somewhat higher on the IV pressure glove ball bearing (Fig. 32a) compared to the EV pressure glove ball bearing (Fig. 32b). However, an overall assessment of the surfaces of several ball bearings shows no clear differences in scratch density between ball bearings from the two glove types. The origin of the scratches is unknown, but their occurrences on the ball bearings from the IV glove, which was never worn on the lunar surface, suggests they are not produced from wear effects from lunar soil.

Short of a more quantitative analysis of the number density, surface depth and morphology of the scratches and abrasion features on the glove rotation ring wear surfaces, our first-order estimation is that there is no sign of increased wear in the EV glove bearing caused by effects from contaminating lunar soil particles. The explanation for this observation can be linked to two possible causes, which cannot be differentiated or preferred based on the present study: Either the combined functions of the glove gauntlet and bearing seals prevented soil particles from entering the bearing race over the time that the glove was in use on the lunar surface, or particles entered the race but were not sufficiently abrasive to cause damage over the duration of exposure, or possibly both factors played a role.

Apollo Command Module LiOH Canister Filters

The three selected Apollo 11 LiOH canister filters were each initially back flushed using 500 ml of 190 proof (95%) laboratory grade ethyl alcohol and then flushed in reverse to remove as much trapped solid material as possible. The resulting residue was centrifuged to separate the solids from the alcohol and the elutriant decanted. The remaining fluid was then evaporated and the dust dried, mounted on 10 mm SEM brass stubs and analyzed by both optical and scanning electron microscopy. To provide a comprehensive picture of the filtrate, four SEM mounts were made for the residues of each filter and were

lightly carbon-coated. SEM images and EDS analyses revealed only a small proportion of lunar grains in the filter materials. As shown in the representative SEM image in Figure 33, the majority of particles are human dander or pieces of fiberglass, but lunar dust particles are nonetheless present. This shows qualitatively that lunar dust particles were present in the environment of the CM following the lunar surface mission.

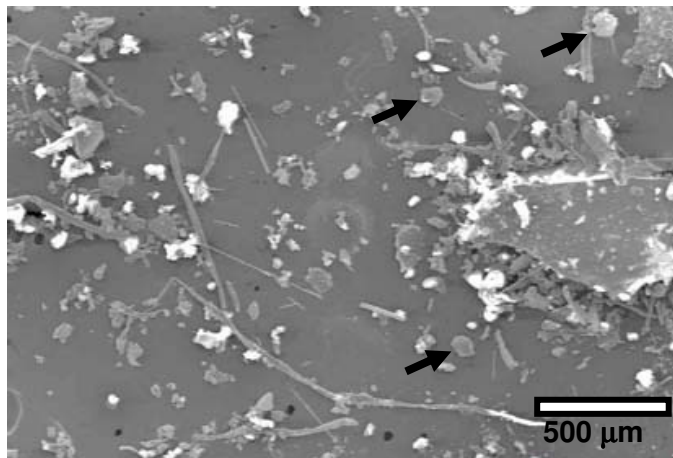


Figure 33. Secondary electron SEM image of particles rinsed from LiOH canister filter. Most particles are human dander or fiberglass but a smaller number are lunar soil particles (arrows).

Analysis and Discussion

Lunar Dust Retention and Distribution on the Apollo Spacesuits

One set of objectives of the current study was to understand the factors that determine how lunar dust particles are physically held as contaminants on the Apollo spacesuits (Table 1). This included assessing variations in the relative amounts of lunar dust on different areas of the spacesuit, and whether there were variations linked to the different mineralogical types of particles in the lunar soil. These objectives connect primarily to the issue of spacesuits as systems that intrinsically experience a high degree of direct interaction with the lunar soil, resulting in the suit potentially becoming a prime carrier of lunar dust contamination from the lunar surface back into the pressurized environment of a lander spacecraft or more permanent habitat.

Our results demonstrate that the woven material used to form the outer skin of the Apollo spacesuits, mostly consisting of T-164 Teflon fabric, retained a considerable number of lunar soil particles even 35 years after the spacesuits were returned from the Moon and underwent disassembly and/or physical handling. As used here, the term “considerable” most likely represents concentrations of up to 2.5×10^5 lunar particles per square centimeter of fabric, an estimate based on our SEM observations of the average concentration of lunar grains on our adhesive tape samples from the Apollo 17 spacesuit. This concentration represents particles held loosely enough on the fabric to be removed by adhesive tape, and does not include additional particles that may have penetrated past the outermost fabric layers to become lodged deeper in the fabric layup. It also corresponds to the number of particles retained on the fabric after a degree of post-mission cleaning that almost certainly did not use water or other fluids, but which may have involved an unknown amount of brushing or light use of a vacuum cleaner. Overall, for the Apollo 17 spacesuit at least, the level of lunar dust contamination retained after 35 years we believe is most likely representative of what this particular spacesuit design would retain on a day-to-day operational basis if it were used on an extended mission. Whether this level of dust contamination would be operationally acceptable remains to be determined, but the tape sampling suggests that whatever dust is on the fabric is

relatively loosely held, and could therefore be easily transferred from the spacesuit to the spacecraft environment. With regard to the size of these “transferrable” particles, our baseline measurement of an average particle diameter of 10.5 μm should be taken as an upper estimate, because it does not take into account the sub-set of smaller grains that were excluded from the dataset because EDS analysis could not confirm them as lunar origin, even though such an origin is likely.

We have also obtained some insight, using indirect methods, of variations in the relative levels of lunar soil contamination on different areas of the spacesuit. These indirect methods, consisting of Ti concentrations as measured by ED-XRF as well as gray-level estimates of fabric darkening, correlate well enough with one another to validate their mutual use as indicators of the relative amount of lunar soil latent on the spacesuit fabric. It should be noted, however, that unlike the gray-level estimates, the ED-XRF data likely measure amounts of lunar soil not only on the outermost surface of the fabric, but also amounts held in fabric layers several millimeters below the surface.

The distribution of lunar soil contamination reflected in the Ti analysis map in Figure 24 shows highest concentrations of soil on the lower portion of the spacesuit, particularly the legs, as might be expected, with slightly more soil on the front of the legs as compared to the rear. This result agrees with the notion that the lower front of the spacesuit is closer to the lunar surface and more likely to encounter particles kicked up during walking or other EVA operations. Mission films also show Schmitt losing his balance and falling slightly forward or to the side on some occasions. Two other areas of the spacesuit with higher soil concentrations of soil are the seat and the front and rear of the forearms. We suspect the higher concentrations on the seat are at least partly due to soil particles that became ground into the fabric while Schmitt was seated on the lunar rover, or possibly also in the CM during return to Earth. The fact that the spacesuit lower arms are highly contaminated is intriguing given that this part of the spacesuit is not physically close to the lunar surface. Most likely these areas became contaminated in the course of upper body motions that brought the arms close to surface while Schmitt collected samples, deployed surface equipment, or supported himself when he lost his balance.

Apart from the absolute and relative amounts of lunar soil on the Apollo 17 spacesuit, the current study has also determined that the Apollo spacesuit outer fabric retains a population of latent lunar dust particles that is not necessarily representative of the soil type at the mission locality. On a relative volume basis at least, retention of lunar soil glass particles appears to be less efficient relative to actual mineral grains, with pyroxene showing the highest volumetric proportion relative to other lunar minerals. While these findings remain incompletely understood, we suspect that they are more a reflection of the resistance of a particular particle to removal from the fabric by fracture and breakage when the fabric is physically brushed or rubbed, as opposed to any major differences in surface adhesion properties. However, this potentially important findings should be investigated in future tests.

Role of Lunar Dust in Wear Performance of Spacesuit Materials

A second set of study objectives pertained to the actual engineering performance of the Apollo spacesuits with emphasis on how this performance was impacted by lunar dust. The main area of performance for which data were obtained relate to the physical wear response of the spacesuit outer woven fabrics, particularly the T-164 woven Teflon on the ITMG. The study results document progressive transformation of the spacesuit T-164 Teflon outer fabric from its intact state, to a worn state in which individual Teflon fibers become progressively split and frayed. The SEM observations of the Apollo 12 spacesuit fabric show additionally that as wear progresses there is an increasing transfer of fragments of glass fibers from the underlying beta cloth to the exposed surface of the Teflon fabric. This indicates that physical wear is also occurring in underlying layers of the fabric layup, and that the beta cloth in particular is adding an undesirable additional load of free particles to the spacesuit surface.

The SEM observations of the Apollo 12 T-164 Teflon fabric swatches are supplemented by the more extensive series of light-optical binocular microscope images of the T-164 Teflon fabric on the Apollo 17 spacesuit (Fig. 16). Although they are of lower resolution relative to the SEM observations, these images provide additional microscopic documentation of progressive separation and fraying of the yarn fibers

comprising the weave. We believe a notable feature of the Figure 16 images is that the more abraded and frayed areas of the Teflon yard also show evidence of being darkened by trapped lunar dust particles, evidence that progressive fabric wear allows more lunar dust particles to be retained by the fabric. This connection is also supported by an indication in Figure 16 that the imaged areas with higher soil contamination levels measured by their Ti concentration also appear to be more worn. Thus, physical wear and abrasion of spacesuit fabrics would appear to have the undesirable consequence of increasing the fabric's capacity to retain lunar dust contamination.

Results on the wear performance of the outer material components of the Apollo 17 EV pressure glove showed a number of effects of physical abrasion of all components. In particular, the SEM observations of the Chromel R metal fabric component showed a notable susceptibility of the Chromel R fibers to physical abrasion. The number of nicks, scratches and pits was extensive enough to indicate that this fabric was showing overall poor wear performance relative to its relatively short period of use on the lunar surface. Whether this performance was any worse than what polymer fibers would have experienced on such a high-use part of the spacesuit remains to be determined.

Although it is clear that the Apollo spacesuit outer fabric materials experienced significant wear during their mission life, our information on the exact role of lunar soil particles in causing or accelerating this wear remains somewhat incomplete. Because the spacesuit ITMG was typically worn for at least as much time in the CM and LM as it was on the lunar surface (Table 3), it is possible that some of the fabric wear and abrasion effects observed were produced when the spacesuit was pressed or rubbed against hard surfaces. On the microscopic scale, however, the common observation of lunar dust particles wedged between fibers in highly worn areas of fabric does suggest a role for the particles in promoting wear. This hypothesis is further supported by the previously-discussed correlation between overall fabric contamination level measured by ED-XRF and fabric wear as indicated by light-optical imaging. Overall, we believe our study results show a significant, notable role for lunar soil interactions in causing physical wear of spacesuit fabrics and other components, but the precise role of dust relative to other factors, over a given mission lifetime and operational scenario, remains a key topic for future investigations.

Implications for Future Spacesuit Design and Lunar Surface Operations

Use of Woven Fabrics

Woven fabrics were the foundation for the functional design of the Apollo spacesuits. Even 35 years after the lunar missions, these fabrics were found to contain a significant contamination level of lunar dust particles. There is evidence that retention of these contaminating particles on the spacesuit is promoted by interaction between the dust particles and the weave of the spacesuit fabrics. It follows by implication that alternatives to woven fabrics should probably be found for future spacesuits. If future woven fabrics are employed, they should employ appropriate surface coatings to keep particles from entering and penetrating the fabric weave. As might be expected, we have also found that fabric wear and susceptibility to lunar dust contamination go hand-in-hand, implying that toughness and wear resistance of any future spacesuit fabrics will be essential to providing dust resistance.

Spacesuit Coveralls for Dust Mitigation

Current discussions of ways to mitigate dust effects on spacesuits over extended lunar missions have considered employing a one-time-use lightweight coverall garment to protect spacesuit outer systems and surfaces. Our findings for the distribution of lunar dust on the Apollo spacesuits show normal EVA operations will result in even the uppermost parts of the spacesuit, including the arms, becoming exposed to high levels of soil contamination. Therefore, a partial cover garment protecting only the lower half of the spacesuit will not be sufficient, and any successful design must cover the entire spacesuit, including the arms.

Spacesuits as a Selective Dust Carrier

To the extent that the different mineralogical components of the lunar soil may ultimately be shown to have different levels of toxic threat to lunar crews, or physical threats to lunar surface systems, the composition of lunar soil at a given exploration site may be a factor in assessing risk factors for various mission scenarios. Our findings clearly show that the soil composition at a given mission site is not necessarily what will be brought into a spacecraft or habitat environment by the spacesuit after a given EVA. Future spacesuits will need to be tested with respect to their selective carrying capacity for different lunar soil components so that contamination risks to the spacecraft environment can be adequately assessed.

ED-XRF as an Ongoing Dust Assessment Tool

We successfully used ED-XRF as a tool to make an indirect assessment of the amount of lunar soil latent on the Apollo 17 spacesuit. Once properly calibrated, the technique provides rapid results and is easily portable. This technology should be evaluated further for applications where dust contamination is being evaluated in lunar analog-based systems testing or on the lunar surface itself.

Performance of Apollo-Era Rotating Pressure Seals in the Lunar Dust Environment

We found no evidence that the sealed 360° wrist rotation bearing on the EV pressure glove was compromised by lunar dust. It is quite possible that this Apollo-era design may be a useful baseline for designing dust-resistance rotating pressure seals for future lunar surface systems.

Summary and Conclusions

- SEM observations of swatches of the outermost T-164 Teflon fabric from the Apollo 12 LMP ITMG identified a signature of progressive and accelerated fabric wear that tests show is most likely due to effects from lunar soil particles. The observations document penetration of some lunar soil particles through the fabric of an insignia patch and show that lunar soil particles cause separation of fibers in the fabric weave.
- Based on systematic sampling of particles from the outermost fabric surface of the Apollo 17 LMP ITMG using an adhesive tape extraction method combined with SEM examination, the mean grain size of lunar soil particles on the fabric was determined to be less than 10.4 μm . Based on grain number counts, the lunar grain population on the fabric is dominated by equal amount of plagioclase feldspar monomineralic grains and glass particles. The latter consist predominantly of agglutinitic glass fragments. Lesser amounts of pyroxene, ilmenite and olivine also occur. When the proportions of grain types based on grain number are recalculated to a modal percent (volume percent) basis, the results show significant modal enrichment of pyroxene on the fabric relative to the modal analysis of Apollo 17 soils. In addition, on a modal basis, glass is much less abundant on the fabric than in the soil. These data point to a measurable selectiveness in the adhesion and retention of certain minerals on the ITMG fabric.
- Based on portable ED-XRF spectroscopy, the Ti content of the fabric of the Apollo 17 LMP ITMG has been identified as a practical compositional marker for the level of fabric contamination by lunar soil. Titanium content shows a significant positive correlation with indirect assessment of fabric contamination based on visual gray scale color.
- SEM examination of the Apollo 17 EV pressure glove revealed significant abrasion of the Chromel R outer covering as well as significant trapping of what are likely to be lunar dust particles in the Chromel R weave. The observations indicate that lunar soil probably passed through the outer Chromel R fabric layers, and suggest that over long exposure the particles would likely contaminate underlying fabric layers as well. Such contamination could accelerate wear in these underlying fabric layers.
- Disassembly and SEM examination of the wear surfaces in the wrist rotation bearings in the Apollo 16 IV and EV pressure glove assemblies show no measurably-increased wear or abrasion in the EV

glove as compared to the IV glove. This suggests that even though the EV glove was worn in the dusty lunar environment, either dust particles did not penetrate the bearing seal or if they did they were not sufficiently abrasive to produce accelerated wear for the duration of exposure.

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